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Carbon Capture Materials and Adsorption Performance in Cement Plant Emissions

Amelia N. Foster*

Department of Civil, School of Engineering, University of Southampton, Southampton, England, United Kingdom

Corresponding author: amelia.n.foster@southampton.ac.uk

Abstract

The cement industry is a massive contributor to global anthropogenic carbon dioxide emissions, primarily due to the chemical calcination of limestone and the combustion of fossil fuels required to reach high kiln temperatures. Implementing carbon capture technologies in this sector is hindered by the exceptionally harsh conditions of cement plant flue gas, which is characterized by high carbon dioxide concentrations alongside severe contaminants such as sulfur dioxide, nitrogen oxides, particulate matter, and significant moisture. This paper presents a comprehensive reliability testing of several promising solid carbon capture materials, specifically evaluating their adsorption performance and long-term cyclic stability under simulated cement plant emission conditions. Through rigorous experimental evaluation in a custom-designed dynamic fixed-bed reactor, we assess the equilibrium adsorption capacities, kinetic behaviors, and degradation profiles of amine-functionalized mesoporous silica, Zeolite 13X, and a highly porous metal-organic framework. The study focuses heavily on the irreversible degradation mechanisms triggered by acid gas competitive adsorption and moisture-induced structural collapse. The findings indicate that while initial adsorption capacities are substantial across all candidates, the presence of sulfur dioxide drastically reduces the operational lifespan of amine-based and metal-organic materials. Zeolite 13X demonstrates superior thermal and chemical resilience but suffers from severe competitive adsorption with water vapor. The research provides critical insights into the material selection and process optimization necessary for deploying robust, economically viable carbon capture systems in heavy industrial applications, emphasizing the need for extensive pre-treatment or advanced composite materials to ensure operational reliability.

Keywords: Carbon Capture; Cement Industry; Adsorption Performance; Solid Sorbents; Material Reliability

1. Introduction

1.1 Background and Industrial Context

The global imperative to mitigate climate change requires rapid and extensive reductions in greenhouse gas emissions across all sectors of the global economy. Among these sectors, heavy industry poses a unique and profound challenge due to the inherent nature of its manufacturing processes. The cement industry, in particular, is responsible for approximately eight percent of global anthropogenic carbon dioxide emissions, a figure that is largely driven by the fundamental chemistry of clinker production [1]. Unlike the power generation sector, where emissions are almost entirely derived from the combustion of fossil fuels, cement manufacturing generates carbon dioxide through both fuel combustion and the calcination of calcium carbonate into calcium oxide. This dual source means that even a complete transition to renewable energy for heating would only address a fraction of the emissions, making the capture of carbon dioxide directly from the flue gas an absolute necessity for achieving net-zero targets [2].

The integration of carbon capture technologies into cement plants is severely complicated by the highly complex and aggressive nature of the exhaust gases. Cement plant flue gas typically contains carbon dioxide concentrations ranging from fourteen to thirty-three percent by volume, which is significantly higher than the emissions from natural gas or coal-fired power plants. However, this high concentration is accompanied by

elevated levels of sulfur dioxide, nitrogen oxides, volatile organic compounds, trace heavy metals, and a substantial load of abrasive particulate matter [3]. Furthermore, the moisture content can be highly variable depending on the raw materials used in the kiln. Traditional liquid amine scrubbing, which is the most mature technology for post-combustion carbon capture, faces insurmountable challenges in this environment. Liquid amines are highly susceptible to oxidative and thermal degradation, and the presence of sulfur dioxide leads to the formation of heat-stable salts that irreversibly consume the active amine solvent, drastically increasing operational costs and creating hazardous waste streams [4].

Consequently, there has been a massive shift in academic and industrial focus toward the development and deployment of solid sorbents for carbon capture. Solid adsorption technologies promise significantly lower regeneration energy requirements, reduced corrosion issues, and the potential for a wider operating temperature window. A myriad of advanced materials, including zeolites, activated carbons, metal-organic frameworks, and organically modified silicas, have demonstrated exceptional carbon dioxide uptake capacities in pristine, laboratory-controlled environments. However, the critical bottleneck preventing the industrial rollout of these materials is a profound lack of reliability data under realistic, multi-component flue gas conditions.

1.2 Research Objectives and Scope

The primary objective of this research is to rigorously evaluate the reliability and adsorption performance of leading carbon capture materials when exposed to a simulated cement plant emission profile. This study moves beyond idealized single-gas adsorption isotherms to investigate the complex, dynamic interactions that occur when candidate materials are exposed to high concentrations of carbon dioxide alongside critical contaminants. By systematically introducing moisture, sulfur dioxide, and nitrogen oxides into the gas stream, this research aims to isolate the specific degradation mechanisms that compromise material longevity and structural integrity.

To achieve this, the investigation focuses on three distinct classes of solid sorbents that represent the current state-of-the-art in carbon capture technology. The first is an amine-functionalized mesoporous silica, chosen for its high chemical affinity for carbon dioxide and theoretical tolerance to moisture. The second is Zeolite 13X, a commercial benchmark known for its exceptional thermal stability and rapid adsorption kinetics. The third is a representative metal-organic framework, selected for its incredibly high surface area and tunable pore chemistry. By subjecting these materials to extended cyclic testing, alternating between adsorption and thermal desorption phases, the study quantifies the capacity retention rates over time.

Understanding the reliability of these materials is not merely a theoretical exercise but a vital step toward the engineering of scalable industrial systems. The economic viability of a solid sorbent-based capture plant hinges entirely on the lifespan of the adsorbent material. If a material requires replacement after only a few hundred cycles due to poisoning by acid gases, the operational expenditures will render the technology unfeasible regardless of its initial capture efficiency. Therefore, this research provides a vital bridge between fundamental materials science and applied chemical engineering, offering a comprehensive assessment of how these advanced materials behave under the punishing realities of cement manufacturing emissions.

2. Literature Review and Theoretical Framework

2.1 Evolution of Carbon Capture Materials

The transition from liquid chemical absorption to solid physical and chemical adsorption represents a paradigm shift in environmental engineering. In the context of post-combustion capture, solid sorbents function by selectively accumulating carbon dioxide molecules on their internal and external surfaces. This accumulation can occur via physisorption, which relies on weak van der Waals forces and electrostatic interactions, or via chemisorption, which involves the formation of reversible covalent bonds between the carbon dioxide and specific functional groups on the material surface [5]. Extensive research over the past two decades has generated a vast array of porous solids, each with distinct advantages and inherent vulnerabilities.

Zeolites are among the most extensively studied physisorbents. These crystalline aluminosilicates possess highly uniform microporous structures and an inherent polarity that makes them highly selective for quadrupolar molecules like carbon dioxide. Literature indicates that Zeolite 13X and Zeolite 5A exhibit phenomenal uptake capacities at low pressures and ambient temperatures [6]. However, the strong electrostatic

fields within the zeolite framework that attract carbon dioxide also exhibit an even stronger affinity for polar water molecules. Numerous studies have documented that the presence of even trace amounts of humidity drastically reduces the carbon dioxide capacity of zeolites due to competitive adsorption, where water molecules preferentially occupy the active sites [7]. This fundamental limitation necessitates extensive dehydration of the flue gas prior to contact with the zeolite bed, imposing a significant energy penalty on the overall capture process [8].

Metal-organic frameworks represent a newer class of materials characterized by metal nodes coordinated to organic linkers, creating highly ordered, infinitely tunable, porous networks. The literature highlights metal-organic frameworks as possessing the highest known surface areas of any porous material, enabling theoretically massive carbon dioxide storage capacities [9]. Researchers have successfully synthesized thousands of distinct framework topologies, optimizing pore sizes to perfectly match the kinetic diameter of a carbon dioxide molecule. Despite these extraordinary properties, the Achilles heel of most metal-organic frameworks is their poor hydrothermal and chemical stability. The coordinative bonds between the metal ions and the organic linkers are often susceptible to hydrolysis, leading to rapid structural collapse when exposed to the moisture levels typically found in industrial exhaust streams [10].

Amine-functionalized silicas attempt to combine the robust structural properties of inorganic supports with the highly selective chemical reactivity of liquid amines. By grafting or impregnating polyamines onto high-surface-area mesoporous silica, researchers have created chemisorbents that can operate effectively even in the presence of water vapor. In fact, literature suggests that moisture can sometimes enhance the capture efficiency of amine-modified materials through the formation of bicarbonate species, rather than the carbamate species formed in dry conditions [11]. This moisture tolerance makes them highly attractive for industrial applications.

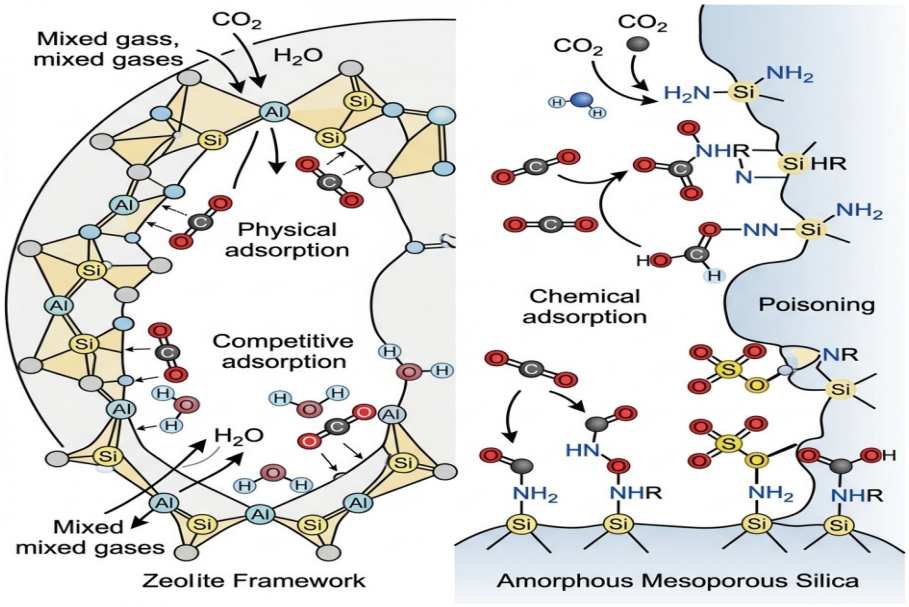

Figure 1: Comprehensive Schematic of Adsorption and Degradation Mechanisms

2.2 Degradation Mechanisms in Harsh Industrial Environments

While the initial adsorption capacity of a material is important, its cyclic stability under realistic conditions is the true determinant of industrial viability. Cement plant flue gas introduces an array of chemical species that actively attack and degrade solid sorbents. The most detrimental of these are sulfur oxides, primarily in the form of sulfur dioxide. Sulfur dioxide is a strong acid gas that competes directly with carbon dioxide for basic adsorption sites.

In amine-functionalized materials, sulfur dioxide reacts with the amine groups to form highly stable sulfite and sulfate complexes. These complexes are thermodynamically incredibly stable and cannot be broken under the relatively mild thermal conditions used for carbon dioxide desorption. This leads to an irreversible loss of active capture sites, a phenomenon widely known as sulfur poisoning [12]. The rate of amine deactivation is

directly proportional to the concentration of sulfur dioxide in the gas stream and the total exposure time. Previous kinetic models have shown that even single-digit parts-per-million concentrations of sulfur dioxide can halve the functional capacity of an amine sorbent within a few thousand operational cycles [13].

Nitrogen oxides present another significant threat, albeit through a different mechanism. Nitrogen dioxide, in particular, is a potent oxidizing agent. When exposed to solid sorbents at elevated regeneration temperatures, it can trigger the oxidative degradation of organic components, including the linkers in metal-organic frameworks and the polyamine chains in supported liquid materials [14]. The oxidation breaks the polymer chains, resulting in the volatilization of the active groups and a subsequent drastic drop in capture efficiency.

Furthermore, the physical structure of the solid sorbents can be compromised by the extreme thermal cycling required for continuous operation. Temperature swing adsorption processes repeatedly heat the material to drive off the captured carbon dioxide and then cool it to resume capture. Over thousands of cycles, the differences in thermal expansion coefficients between the active materials and their structural supports can lead to microscopic fracturing, attrition, and the generation of fine dust. This not only reduces the volume of available active material but also increases the pressure drop across the fixed bed, eventually requiring a complete shutdown of the plant for bed replacement [15]. Understanding the synergistic effects of these chemical and physical degradation pathways is essential for predicting material reliability in the context of cement emissions.

3. Methodology and Experimental Design

3.1 Material Preparation and Characterization

To conduct a robust reliability assessment, three distinct classes of solid sorbents were prepared, ensuring that the synthesized materials were highly representative of current industrial and academic standards.

The first material, an amine-functionalized mesoporous silica, was synthesized using a wet impregnation method. Commercial mesoporous silica with a nominal pore size of fifteen nanometers was selected as the support structure due to its high surface area and mechanical robustness. The silica support was dehydrated under a vacuum at elevated temperatures to remove any physisorbed water. Subsequently, tetraethylenepentamine was dissolved in methanol, and the silica support was slowly added to the solution under continuous vigorous stirring. The solvent was then slowly evaporated under reduced pressure, allowing the polyamine to evenly coat the internal pore surfaces of the silica. The final composite was engineered to contain an amine loading of forty weight percent, balancing maximum carbon dioxide capacity with the need to maintain open pore channels for gas diffusion.

The second material utilized was a commercial-grade Zeolite 13X in the form of spherical pellets. To ensure experimental consistency, the zeolite pellets were subjected to an extensive activation protocol prior to any testing. This involved heating the material to four hundred degrees Celsius under an inert nitrogen flow for twelve hours to completely desorb atmospheric moisture and trace volatile organic compounds. The pristine structural integrity and internal surface area of the activated zeolite were confirmed using standard nitrogen physisorption techniques, verifying a micropore volume consistent with high-quality crystalline aluminosilicates.

The third material was a highly moisture-stable metal-organic framework, specifically the zeolitic imidazolate framework known as ZIF-8. While many metal-organic frameworks are highly sensitive to water, ZIF-8 is noted for its relative hydrothermal stability, making it a viable candidate for this study. The framework was synthesized rapidly at room temperature by mixing solutions of zinc nitrate hexahydrate and 2-methylimidazole in a solvent mixture of methanol and water. The resulting precipitate was collected via centrifugation, washed extensively with pure methanol to remove unreacted precursors, and dried thoroughly under vacuum.

Table 1: Composition of Simulated Cement Plant Flue Gas

Gas Component	Concentration	Function in Experiment
Carbon Dioxide	18.0 %	Target adsorbate
Nitrogen	75.8 %	Carrier / Background gas
Oxygen	4.0 %	Oxidative degradation testing

Gas Component	Concentration	Function in Experiment
Water Vapor	2.0 %	Moisture competitive adsorption
Sulfur Dioxide	500 ppm	Acid gas poisoning
Nitrogen Monoxide	1500 ppm	Oxidative / Acidic poisoning

3.2 Simulated Flue Gas Environment and Reactor Setup

Testing the reliability of these materials required the design and construction of a highly specialized dynamic fixed-bed reactor system capable of precisely simulating the extreme conditions of a cement plant exhaust stream. The core of the system consisted of a vertical, heavily insulated stainless-steel column housing a central quartz tube where the sorbent materials were packed. The reactor was equipped with highly sensitive, multi-zone electric heating jackets that allowed for exact temperature programming, crucial for both the adsorption phases and the higher-temperature desorption phases of the cycles.

The complex gas mixtures were generated using a custom-built manifold featuring an array of precision thermal mass flow controllers. As detailed in the table above, the simulated cement flue gas was predominantly composed of nitrogen and carbon dioxide, representing the bulk flow. The flow controllers allowed for the accurate introduction of oxygen, sulfur dioxide, and nitrogen monoxide from certified calibration gas cylinders. To introduce moisture into the stream in a highly controlled manner, a portion of the carrier gas was diverted through a heated water bubbler saturator. The temperature of the saturator was tightly regulated by a circulating thermostatic bath, ensuring that the exact required vapor pressure of water was maintained to achieve the target two percent moisture content in the final mixed gas stream. All gas transfer lines downstream of the moisture saturator were continuously heated using specialized tracing tape to prevent any premature condensation of water vapor or the formation of highly corrosive liquid acids before the gas reached the adsorbent bed.

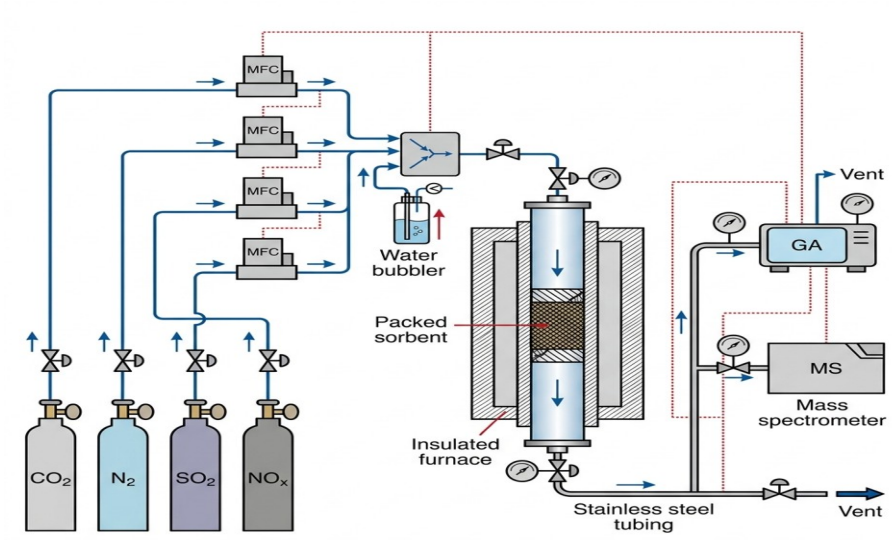

Figure 2: Detailed Schematic of the Dynamic Fixed

3.3 Reliability Testing and Cyclic Protocols

The core methodology for evaluating the materials relied on dynamic breakthrough experiments combined with long-term temperature swing adsorption cycling. In a standard breakthrough test, a known mass of the sorbent material was packed into the quartz reactor tube, supported by high-temperature quartz wool to prevent any entrainment of the particles into the gas stream. The packed bed was first purged with pure nitrogen and brought to a stable baseline adsorption temperature of forty degrees Celsius, which is highly representative of the gas temperature exiting a cement plant's wet scrubber system.

Once the baseline was established, the simulated flue gas mixture was introduced into the reactor at a constant volumetric flow rate. The composition of the gas exiting the top of the reactor bed was continuously monitored and quantified using a highly calibrated, high-speed gas chromatograph equipped with both thermal

conductivity and flame photometric detectors. The adsorption phase continued until the concentration of carbon dioxide in the effluent stream precisely matched the inlet concentration, a state known as complete bed saturation or equilibrium. The total equilibrium adsorption capacity of the material was calculated by mathematically integrating the area above the measured breakthrough curve over the duration of the experiment.

Following saturation, the bed transitioned to the desorption and regeneration phase. The flow of the simulated flue gas was halted, and the reactor was purged with pure, dry nitrogen while the internal temperature was rapidly ramped to one hundred and twenty degrees Celsius. The elevated temperature provided the necessary thermal energy to break the physical or chemical bonds holding the carbon dioxide to the sorbent. The reactor was held at this elevated temperature until the gas analyzer confirmed that no carbon dioxide was being released, indicating complete regeneration of the bed. The bed was then actively cooled back to forty degrees Celsius to begin the next cycle.

To rigorously test the reliability and degradation of the materials, this temperature swing adsorption process was repeated continuously for one hundred consecutive cycles for each material candidate. The data acquisition system recorded the exact adsorption capacity during every single cycle. This extensive dataset allowed for a highly granular analysis of the progressive degradation rates and the specific capacity retention of the materials when subjected to the multi-component chemical attacks characteristic of the simulated cement plant environment.

4. Results and Adsorption Performance Analysis

4.1 Initial Adsorption Capacities and Kinetics

The preliminary evaluation focused on the pristine adsorption performance of the materials during the first experimental cycle, providing a baseline metric for their theoretical maximum capacities under the simulated conditions. The data revealed significant variance in both the total carbon dioxide uptake and the adsorption kinetics among the three candidate materials.

The amine-functionalized mesoporous silica demonstrated a highly robust initial capture performance, achieving an equilibrium adsorption capacity of approximately two point eight millimoles of carbon dioxide per gram of sorbent. The breakthrough curve for the amine material exhibited a distinct, dual-stage kinetic profile. The initial phase of the curve was exceptionally sharp, indicating a very short mass transfer zone and rapid surface reaction between the carbon dioxide and the readily accessible primary amines located on the outer surface of the silica particles. This was followed by a more gradual approach to total saturation, a kinetic limitation driven by the slower diffusion of carbon dioxide into the deeper internal mesopores where the secondary and tertiary amines were located. Notably, the presence of two percent moisture in the simulated flue gas stream appeared to slightly enhance the initial uptake kinetics of this material, confirming literature suggestions that water molecules assist in the formation of bicarbonate species, thereby increasing the stoichiometric efficiency of the amine groups [16].

Zeolite 13X exhibited a remarkably high initial uptake capacity in the very first minutes of the experiment, capturing carbon dioxide at a rate faster than either of the other two materials. However, its overall equilibrium capacity for carbon dioxide was severely stunted, capping at one point five millimoles per gram. This massive underperformance relative to its theoretical dry capacity was unambiguously attributed to the severe competitive adsorption of water vapor. The highly polar nature of the aluminosilicate framework resulted in a preferential binding of water molecules, which rapidly occupied the strongest adsorption sites and sterically hindered the entrance of carbon dioxide molecules into the micropore network [17]. The breakthrough curve for Zeolite 13X showed carbon dioxide breaking through the bed much earlier than anticipated, while the water vapor continued to be adsorbed, clearly demonstrating the displacement effect.

The ZIF-8 metal-organic framework presented a moderate initial equilibrium capacity of one point nine millimoles per gram. Its breakthrough profile was characterized by a very broad mass transfer zone, indicating slower overall kinetics compared to the commercial zeolite. This slower uptake is largely dependent on the specific pore aperture size of the framework. While the internal cavities of ZIF-8 are expansive, the restrictive

windows connecting these cavities force the gas molecules to overcome a significant diffusion barrier, a process heavily dependent on the partial pressure of the target gas.

Table 2: Comparison of Adsorption Capacities and Capacity Retention Rates

Sorbent Material	Initial Capacity (mmol/g)	Cycle 100 Capacity (mmol/g)	Capacity Retention Rate
Amine-Silica Composite	2.85	1.12	39.3 %
Commercial Zeolite 13X	1.50	1.41	94.0 %
ZIF-8 Framework	1.95	0.35	17.9 %

4.2 Cyclic Reliability and Structural Degradation

The true industrial viability of these materials is dictated entirely by their performance over extended cycling. The results of the one-hundred-cycle reliability testing, summarized in the table above, highlight profound vulnerabilities in highly engineered materials when exposed to the relentless chemical attacks typical of cement plant emissions.

The most catastrophic degradation was observed in the metal-organic framework. By the one-hundredth cycle, the ZIF-8 material had retained less than eighteen percent of its initial carbon dioxide capacity. Post-experiment structural characterization of the spent material using X-ray diffraction techniques revealed a near-complete loss of long-range crystalline order. This massive structural collapse was driven by a combination of the mild hydrothermal stress from the moisture during the elevated temperature desorption phases and, more critically, the highly destructive attack by sulfur dioxide [18]. The acidic sulfur dioxide molecules aggressively coordinated with the zinc nodes of the framework, cleaving the bonds with the imidazole linkers and permanently destroying the porous architecture. This extreme lack of chemical reliability entirely disqualifies this specific framework from use in untreated heavy industrial flue streams.

The amine-functionalized silica also suffered severe and continuous degradation, retaining only thirty-nine percent of its initial capacity at the conclusion of the testing regimen. The primary mechanism of failure for this chemisorbent was unambiguous sulfur poisoning. Throughout the cycling, the sulfur dioxide present in the simulated gas stream reacted irreversibly with the basic amine sites, forming heavily cross-linked urea and sulfate structures [19]. Because the thermal energy provided during the one-hundred-and-twenty-degree desorption phase was entirely insufficient to break these highly stable sulfur-amine bonds, the functional groups were permanently consumed. The capacity drop was near-linear over the first fifty cycles as the most accessible surface amines were poisoned, followed by a slight leveling off as the sulfur dioxide had to diffuse deeper into the silica pores to find unreacted active sites. Additionally, a minor degree of oxidative degradation caused by the nitrogen oxides likely contributed to the volatilization of the shorter polyamine chains, further depleting the active capture mass [20].

4.3 Resilience of Inorganic Physisorbents

In stark contrast to the dramatic chemical failures of the highly engineered functional materials, the commercial Zeolite 13X demonstrated extraordinary cyclic reliability. While its initial working capacity was heavily suppressed by the presence of moisture, the capacity it did exhibit proved to be incredibly stable. After one hundred cycles, the zeolite retained ninety-four percent of its initial operational capacity.

The inorganic crystalline structure of the aluminosilicate proved highly resilient to both the thermal stresses of the rapid temperature swings and the acidic environment. Unlike the amine groups or the metal-organic coordinative bonds, the highly stable silicon-oxygen and aluminum-oxygen bonds of the zeolite framework are not readily attacked by sulfur dioxide or nitrogen oxides under these moderate temperature conditions [21]. The slight six percent drop in capacity over the duration of the test was largely attributed to the slow, progressive accumulation of strongly physisorbed water deep within the microporous network that was not fully driven off during the relatively brief thermal regeneration phases.

These analytical results present a classic engineering trade-off. The materials designed for maximum chemical selectivity and high capacity are fundamentally fragile and highly susceptible to irreversible poisoning by the very contaminants that define cement plant emissions. Conversely, the robust, traditional materials that can easily withstand the harsh physical and chemical environment suffer from severe competitive adsorption issues that limit their overall efficiency. The reliability testing emphatically demonstrates that

applying raw capture materials directly to complex flue gases results in rapid performance degradation, necessitating a reevaluation of systemic design approaches.

5. Conclusion and Implications

5.1 Summary of Experimental Findings

This comprehensive study systematically evaluated the reliability and adsorption performance of three leading classes of solid carbon capture materials under the highly demanding, multi-component conditions characteristic of cement plant emissions. By utilizing a highly controlled dynamic fixed-bed reactor system to simulate the exact thermal, moisture, and acid-gas profiles of industrial exhaust, the research successfully bridged the gap between idealized laboratory performance and realistic industrial application. The experimental data conclusively demonstrate that the presence of sulfur dioxide and moisture acts as the primary limiting factors for material longevity and overall process efficiency.

The highly engineered metal-organic framework, despite its theoretically massive surface area, proved entirely unsuitable for this specific application due to its rapid and catastrophic structural collapse when exposed to acidic trace gases. The amine-functionalized mesoporous silica, which initially demonstrated superior carbon dioxide uptake and favorable kinetics due to its moisture tolerance, suffered from severe, irreversible sulfur poisoning. The permanent consumption of its active chemical sites by sulfur dioxide resulted in a massive loss of capture capacity over just one hundred operational cycles, rendering it economically unviable for long-term deployment without aggressive upstream gas purification. Ultimately, the commercial Zeolite 13X was the only material to exhibit structural and operational reliability, maintaining exceptional capacity retention over the extended testing period. However, its overall effectiveness was severely compromised by the competitive adsorption of water vapor, which dramatically suppressed its working carbon dioxide capacity.

5.2 Industrial Relevance and Future Perspectives

The implications of this reliability testing are profound for the future of carbon capture in the heavy manufacturing sector. The findings mandate a significant shift in how capture facilities must be engineered. It is clear that no single currently available material possesses both the chemical resilience to withstand acid gas attacks and the high specific capacity required to make the process economically efficient in the presence of moisture [22]. Therefore, the successful deployment of solid sorbent systems in cement plants will absolutely require a multi-stage approach.

Future industrial implementations must integrate robust, dedicated pre-treatment scrubbers to aggressively remove sulfur dioxide and nitrogen oxides down to single-digit parts-per-million levels before the flue gas ever reaches the primary carbon dioxide capture bed. Alternatively, process engineers must focus on developing advanced thermal or vacuum swing cycles specifically tailored to dehydrate the gas stream efficiently, allowing robust physisorbents like zeolites to operate at their maximum theoretical potential. The development of advanced, hierarchically structured composite materials that utilize a highly resilient outer shell to protect a high-capacity, chemically sensitive inner core represents a highly promising avenue for future research. By thoroughly understanding the precise degradation mechanisms detailed in this study, the scientific and engineering communities can better design the next generation of resilient materials and integrated processes required to successfully decarbonize the critical global cement industry.

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