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EVALUATION OF AMINE-FUNCTIONALISED MACROPOROUS ALUMINIUM FOAM FOR CARBON CAPTURE AND ENVIRONMENTAL MANAGEMENT

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ABSTRACT

The increasing concentration of atmospheric carbon dioxide (CO_2), mainly driven by fossil fuel combustion, necessitates the development of efficient carbon capture technologies. This study evaluates the potential of amine-functionalised macroporous aluminium foam as a novel solid adsorbent for post-combustion CO_2 capture. Three aluminium foams (C_1, C_2, and C_3) with varying pore sizes were functionalised using monoethanolamine (MEA) via physical impregnation. Characterisation confirmed successful grafting of amine groups, with increased N-H and C-N vibrational peaks corresponding to higher amine loading of 39%. Analysis revealed a direct relationship between MEA content and CO_2 adsorption capacity, with C3-MEA-x achieving the highest capture efficiency of 0.014 g CO_2/g adsorbent. The findings revealed the importance of foam morphology in amine loading and adsorption performance. Despite increased pressure drops at higher loadings, the material demonstrated promising potential for scalable CO_2 capture applications due to its high surface area, structural robustness, and efficient gas flow properties. The study provides a foundation for further developing aluminium foam-based solid sorbents in industrial carbon capture systems for enhanced environmental management.

Keywords: Adsorption, Aluminium foams, Carbon Capture, Monoethanolamine, Functionalised

INTRODUCTION

The sharp rise in atmospheric carbon dioxide (CO_2) levels, primarily driven by the combustion of fossil fuels, is a central factor in global climate change (Mathai and Karanikolos, 2020). Mitigating CO_2 emissions is critical to achieving international climate goals and limiting global temperature rise, as the Intergovernmental Panel on Climate Change (IPCC) emphasises. Carbon capture and storage (CCS) technologies have emerged as essential in reducing CO_2 emissions, particularly from high-emission sectors such as power generation, cement production, and chemical manufacturing (Global CCS Institute, 2012). Solid adsorbent-based systems have gained significant attention among the various capture methods due to their advantages over traditional liquid amine systems, including lower energy consumption, reduced corrosiveness, and better thermal and mechanical stability (Su *et al.,* 2023). Despite these benefits, developing efficient solid adsorbents remains challenging. The ideal material must combine high CO_2 selectivity, fast adsorption and desorption kinetics, structural robustness, and ease of regeneration. In recent years, research has focused on amine-functionalised porous materials, which enable chemisorption of CO_2 through acid-base interactions, even at low partial pressures (Arstad *et al.*, 2008; Zagho *et al.*, 2021).

Support materials play a critical role in determining the performance of these functional adsorbents. Common supports like silica, polymers, and mesoporous carbons often suffer from drawbacks such as poor thermal conductivity, mechanical fragility, and limited scalability, making them less suitable for industrial-scale deployment (Ali *et al.*, 2023). Macroporous aluminium foam has emerged as a promising alternative due to its unique properties. It features a high surface area, interconnected macroporosity, low density, high mechanical strength, excellent thermal conductivity, and corrosion resistance (Mayer *et al.*, 2019; Madgule *et al.,* 2023). These features make it particularly well-suited for gas separation processes, where rapid heat and mass transfer are essential. Functionalising aluminium foam with amine groups, such as primary, secondary, or tertiary, can significantly enhance its CO_2 adsorption capacity by introducing active chemisorption sites on the foam surface. Various techniques, including physical impregnation, covalent bonding, and sol-gel processing, have anchored amines onto the aluminium substrate (Rehman *et al.*, 2019). The open-cell structure of aluminium foam promotes low-pressure drop and efficient gas diffusion, while its thermal conductivity supports energy-efficient regeneration cycles (Mustapha *et al*., 2022). These combined properties suggest that amine-functionalised macroporous aluminium foam could outperform existing solid adsorbents in post-combustion carbon capture settings.

Nevertheless, despite its theoretical promise, this material has not been extensively investigated. Key performance parameters, including adsorption capacity, kinetics, thermal and chemical stability, and renewability, remain underexplored. Moreover, the functionalisation method can affect the distribution, accessibility, and long-term durability of amine groups, ultimately influencing the overall efficiency and practicality of the material in real-world CCS applications. Therefore, there is a clear knowledge gap in developing and evaluating amine-functionalised aluminium foam as a viable adsorbent for industrial CO_2 capture for environmental management. Addressing this gap is crucial to advancing next-generation, scalable, energy-efficient carbon capture systems. This study explores the synthesis, characterisation, and performance of amine-functionalised macroporous aluminium foam. By systematically assessing its CO_2 capture properties, the article seeks to establish a foundation for its potential industrial application in sustainable carbon mitigation efforts for effective environmental management.

METHODOLOGY

Macro-porous Aluminium metal foam samples and their experimental characteristics. The aluminium foam samples used are C_1, C_2, and C_3, with bottleneck structures. The experimental characteristics of these foams are detailed in Table 1 as obtained from Otaru and Samuel (2021).

Table 1: Experimental characteristics properties of pure microporous aluminium foam (before functionalization) (Otaru and Samuel, 2021)

Foam samples	Pore size range (mm)	Mean Pore size (mm)	Mean Connectivity Dw (mm)	Porosity Ɛ	Pressure (bar)	Weight (g)	Height (mm)
C_1	0.5 – 1.0	0.730	178± 13	0.656	1 bar	15.92	34.50
C_2	0.5 – 1.0	0.773	243± 12	0.728	0.33	12.34	34.50
C_3	2.0 – 2.5	2.226	899± 19	0.784	0.27	9.88	34.50
C_1+C_3						25.79	69.00

C_1, C_2, C_3 = 3 Different aluminium foams

Experimental procedure and flow investigation

The experimental flow rig for carbon capture and pressure drop measurement through porous materials, such as aluminium foams, is designed to investigate the flow behaviour of CO_2-air gas mixtures. The pressure drop across pure aluminium metal foam samples was a key factor in evaluating their suitability for CO_2 capture applications. To measure this pressure drop, a differential pressure transducer sensitive within the 0-5 V range was incorporated into the experimental setup. Pressure measurements were taken at a sampling rate of 1 Hz, recording pressure differences across the metal foam samples at varying flow rates. The experiments were started by systematically introducing CO_2 and air into the flow rig. Initially, CO_2 and air were passed through the flow rig at 0 Litres Per Minute (LPM), denoted as U1 and U2, respectively, while recording the voltage readings from the 0-5 V Transducer. These readings establish a baseline voltage for CO_2 and air at rest, or the starting point. Gradually, the air flow rate was increased from 0 to 10 (LPM), in 1 (LPM) increments, while voltage readings were recorded at each combination of CO_2 and air flow rates. The experiment was repeated three times as (v1, v2 and v3) for each combination of gases, and the average of the three voltage readings was recorded as (Volt). The flow rate of the gas mixture for each combination of CO_2 and air flow rates was recorded, using the flowmeter just before the sample holder (U4). This ensures accurate flow rate data for correlation with voltage readings. After the initial experiment, the CO_2 flow rate was increased to 1 (LPM), and the air was passed through the flow rig again, ranging from 0 to 10 (LPM), while voltage readings were recorded. The experiment was continued with the CO_2 flow rate constant at 2 LPM while varying the air flow rate between 0 and 10 LPM. Then, the CO_2 flow rate was kept constant at 3 LPM while the air flow rate was varied between 0 and 10 LPM. The process was continued with a unit increment in the flow rate of CO_2 until 10 LPM while varying the air flow rate between 0 and 10 LPM.

Preparation of Amine Solution:

The primary objective of this process is to modify the surface of the porous aluminium foam samples for applications and potential use in carbon capture. The following steps did this: Precisely 5.0 ml of monoethanolamine (MEA) were measured using a 10 ml measuring cylinder. This measurement corresponds to approximately 6.28 g of MEA. 150 ml of methanol was measured, and the measured methanol weighed approximately 117.12 g. The measured MEA and methanol were combined in a suitable beaker. The mixture of solutions was continuously stirred using a magnetic stirrer at a controlled temperature of 60°C for 15 minutes. This stirring process is crucial to attain a homogeneous mixture of MEA and methanol.

Functionalisation Procedure

The functionalisation process is by physical wet impregnation, which employs MEA and methanol as key materials and relies on various laboratory equipment to achieve the desired results, through the following steps: The aluminium foam samples were cleaned by thoroughly rinsing with methanol solvent. This step is crucial to remove any contaminants and impurities from the surface of the foam. After washing, the aluminium foams were dried at atmospheric temperature for 24 hours. This drying period ensures the foams are entirely free of residual solvent and ready for the process. The cleaned, dried aluminium foam samples were placed into a clean and dry 500 ml glass beaker. The prepared amine solution was introduced into the beaker, ensuring complete submersion of the aluminium foam in the solution. A magnetic stirrer was utilised to continuously agitate the solution, facilitating thorough contact between the foam and the amine solution. The reaction was allowed to proceed for four (4) hours at a controlled temperature of 60°C. During this time, the methanol had evaporated, and the amine was effectively loaded onto the surface of the aluminium foam. After completing the process reaction, the foam was carefully removed from the glass beaker. Subsequently, the foam was put under atmospheric conditions, maintaining a room temperature of 25°C, for approximately four days (72 hours) with observed moisture content. It's noticed that the functionalised porous aluminium foams still have a little moisture, then were further subjected to an oven dryer at 50 °C for three hours to ensure it is wholly and thoroughly dried and to attain a free moisture content and are ready for further analysis and potential use in the research proposal. The foams were weighed to accurately determine the amount of amine (x) successfully loaded onto their surface. The Adsorbents were designated as C1-MEA-x, C2-MEA-x and C3-MEA-x. The loading capacities were determined, and x represents the different load mass fractions of MEA in adsorbents.

Measuring CO_2 Adsorption Capacity

Gravimetric analysis is a precise technique to measure CO_2 absorption by monitoring the weight change of an absorbent material over time. In the context of carbon capture, the material (such as aluminium foam or other porous media) adsorbs CO_2, and the increase in mass is proportional to the amount of CO_2 captured. This was done through the following steps: The adsorbent materials were cleaned and dried to remove contaminants and moisture. This step ensures that the only weight gain observed during the experiment was due to CO_2 adsorption. The adsorbent materials were weighed on the analytical balance to record the initial mass (Minitial) accurately. After setting up the flow rig and placing the aluminium metal foam in a sample holder, the CO_2 gas will be introduced. After passing CO2 and air across the sample's adsorbent, the adsorbent was removed and weighed on the analytical balance to record the change in mass. The weight gain (Δm) corresponds to the amount of CO_2 absorbed by the material. The adsorption capacity of the material

was calculated based on the total weight change. This gave the amount of CO_2 adsorbed relative to the initial mass of the adsorbent, usually expressed as grams of CO_2 per gram of adsorbent (CO_2/g adsorbent).

Functionalisation and Amine Loading

The preparation of the Anime solution and procedure for functionalising primary amine (MEA) onto macro porous aluminium metal foam for three (3) samples, C_1, C_2, and C_3, of different characteristic properties was carried out and designated as C_1-MEA-x, C_2-MEA-x and C_3-MEA-x. This surface modification is expected to enhance the aluminium foam's properties, making it suitable for investigating CO2/Air disposition and potential applications in carbon capture. The resulting amine-functionalised aluminium foam is a highly versatile material that combines aluminium foam's structural integrity with amines' adsorption capabilities (Noorani and Mehrdad, 2023). This composite material offers enhanced adsorption capacity for gases and pollutants like CO_2 and Volatile Organic Compounds (VOCs), making it ideal for environmental remediation, carbon capture, and gas separation. Additionally, it shows promise for catalytic applications, energy storage, and conversion technologies (Liu *et al*., 2019). Overall, this innovative material holds significant potential for addressing challenges in sustainability, environmental protection and management, and energy efficiency across various industries.

RESULTS AND DISCUSSION

Amine loading

This indicates the amount or concentration of amine functional groups chemically bonded or physically adsorbed onto a surface or within a material. In amine-grafted aluminium foam, amine loading refers to the quantity of amine groups attached to the surface or embedded within the foam structure. Amine loading is a critical parameter as it directly influences the material's performance in various applications, particularly in processes like CO_2 capture, catalysis, and adsorption. Higher amine loading typically results in increased active sites available for interaction with target molecules, leading to enhanced performance in CO_2 capture efficiency (Li *et al*., 2019; Choi *et al*., 2021), catalytic activity, or adsorption capacity (Ramli and Ahmed, 2014; Li *et al.,* 2019). The foams were weighed to accurately determine the amount of amine (x) that has been successfully loaded onto their surface, as shown in Table 2

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Table 2: Weight Differences Between Pure and Grafted Samples and Amine Loaded (x).

Aluminium Foam sample	Weight before Grafting (g)	Weight after Grafting (g)				Weight after oven dried (g)	Different in weight (g)	Weight fractions (x) of MEA (%)
		1st day	2nd day	3rd day	4th day			
C_1-MEA-x	15.92	22.95	17.48	17.19	16.53	16.31	0.39	28
C_2-MEA-x	12.34	18.25	14.19	14.02	13.66	13.15	0.81	34
C_3-MEA-x	09.88	14.06	11.06	11.32	10.68	10.38	0.50	39
C_1-MEA-x +C_3-MEA-x	25. 79	37.01	29.08	28.51	27.21	26.69	0.90	33

MEA=Monoethanolamine, C_1-MEA-x= First aluminium foam with amine loading, C_2-MEA-x= Second aluminium foam with amine loading, C_3-MEA-x= Third aluminium foam with amine loading

From the results presented in Table 2, the weight differences between pure and grafted aluminium foam samples treated with amines, particularly MEA (monoethanolamine), are significant. The initial weight of the foam samples (before grafting) varies significantly, ranging from 9.88 g (C_3-MEA-x) to 15.92 g (C_1-MEA-x). This variance could be attributed to the inherent material properties such as pore sizes, porosity and pressure of the aluminium foams. After grafting with MEA, the samples' weights increase significantly, which is expected because the amine is now loaded onto the foam's surface. For example, the weight of sample C_1-MEA-x increases from 15.92 g to 22.95 g after grafting. After oven drying, the foam samples show a weight loss over four days (from the 1st to the 4th day). This drying process is essential to remove any solvent or unreacted materials that could affect the final weight (Ramli and Ahmed, 2014; Li *et al.,* 2019).

C_1-MEA-x drops from 17.48 g (1st day) to 16.31 g (4th day), indicating a loss of 1.17 g during the drying process. Similarly, other samples show weight loss, reflecting the gradual removal of moisture or excess MEA. The differences in weight (g) for each sample, as recorded after drying, could be due to the amount of MEA grafted onto the foam and the efficiency of grafting. For example, C_1-MEA-x has a Weight difference of 0.39 g, implying that a modest amount of MEA was grafted or retained after drying. C2-MEA-x, with a difference of 0.81 g, suggests a higher grafting level than C_1-MEA-x. C_3-MEA-x shows a difference of 0.50 g, while the combined sample C_1-MEA-x + C_3-MEA-x shows a more significant difference of 0.90 g, implying more MEA was loaded onto this sample (Arstad *et al.*, 2008; Noorani and Mehrdad, 2023).

The weight fractions (x) of MEA indicated the relative amount of amine grafted onto the foams. C_1-MEA-x has 28% MEA loading, the lowest among the samples. C_2-MEA-x has a higher MEA loading of 34%, and C3-MEA-x has the highest at 39%. Interestingly, the combined sample C_1-MEA-x + C_3-MEA-x has a 33% MEA loading, slightly lower than the individual C_3-MEA-x but higher than C_1-MEA-x. The difference in amine loading across the samples is due to differences in porosity or surface area between the foam samples (Ramli and Ahmed, 2014). The higher the surface area or porosity, the more MEA could be grafted onto the foam. As indicated from the

experimental result, C_3-MEA-x, having the highest Weight fraction of MEA (39%), suggests that it has a more porous structure or a higher surface area that facilitates better amine loading.

The data suggest that the MEA grafting process is successful, with noticeable increases in weight after grafting. The subsequent reduction in weight after drying indicates that some solvent or unreacted material was lost, but a significant portion of MEA was still retained on the foam surface. The variation in weight fractions between the samples may be due to differences in the foam's surface properties, as Osman *et al.* (2021) reported. Samples with higher weight differences post-drying, such as (C_2-MEA-x and C_3-MEA-x), retained more MEA, likely because they had more available surface area or better compatibility with the amine solution as reported by Hack *et al.* (2022).

These weight differences and amine loadings are crucial for gas adsorption applications, such as CO_2 capture. Foams with higher amine loadings (C_3-MEA-x) may offer better performance in terms of adsorption capacity. In comparison, those with lower loadings (C-MEA-x) may have reduced efficiency but possibly lower material costs, as indicated in the literature from Li *et al.* (2019).

Carbon Capture Performance

The carbon capture performance refers to the capacity of a material or system to efficiently capture and store carbon dioxide (CO_2) from emissions, to minimise the amount of CO_2 released into the atmosphere for sustainable environmental management. The amine-functionalised foams are used for this purpose, as they can chemically or physically adsorb CO_2. The performance of these materials is influenced by several factors, including their surface area, pore structure, and the extent of functionalisation, such as amine loading. Table 3 presents data for the CO_2 absorption capacity of different amine-functionalised adsorbents, with the following key metrics: initial and final masses (Minitial and Mfinal), mass change (ΔM), weight fraction of MEA (x), and CO_2 adsorption capacity in (CO_2/g absorbent). The mass change (ΔM) indicates the amount of CO_2 absorbed by each sample. As we move from C1-MEA-x to C_3-MEA-x, the ΔM values increase progressively from 0.10 g to 0.15 g, which correlates with higher CO_2 adsorption capacity. This suggests that samples with higher amine loading (increased weight fraction of MEA) can adsorb more CO_2, as expected due to the greater number of active sites provided by the amine groups for CO_2 interaction, as found in the work of Li *et al.* (2019) and Choi *et al.* (2021). C_1-MEA-x with the lowest amine loading (28%) shows the lowest mass change (0.10 g) and the lowest CO_2 adsorption capacity (0.006 CO_2/g absorbent). In contrast, C3-MEA-x, with the highest amine loading (39%), exhibits the largest mass change (0.15 g), corresponding to the highest CO_2 adsorption capacity (0.014 CO_2/g adsorbent).

There is a trend, as the weight fraction of MEA (amine content) increases, so does the CO_2 adsorption capacity. C_3-MEA-x, with 39% MEA, shows the highest capacity, confirming that a higher concentration of amine groups enhances CO_2 capture by providing more reactive sites for CO_2 binding as found in the literature (Nelson *et al.,* 2021). Also, the CO_2 adsorption capacity follows the same pattern as the weight fraction of MEA for the first adsorbent, C1-MEA-x (28% MEA) has the lowest capacity at 0.006 CO_2/g adsorbent, follow by C3-MEA-x has the highest capacity at 0.014 CO_2/g adsorbent then C_2-MEA-x (34% MEA) shows an intermediate capacity of 0.010 CO_2/g adsorbent. While the mixed sample (C_1-MEA-x + C_1-MEA-x), with a combined weight fraction of 33% MEA, exhibits a CO_2 adsorption capacity of 0.009 CO_2/g adsorbent, which is close to the capacity of C_2-MEA-x. This suggests combining two lower-functionalised samples can yield similar performance to a single sample with a moderate MEA loading, providing flexibility in material design for CO_2 capture applications. This demonstrates that a higher degree of functionalisation with MEA leads to improved CO_2 adsorption performance as recommended by Hasan *et al.* (2021).

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Table 3: Carbon IV Oxide Adsorption Capacity Of Different Amine-Functionalised Adsorbents

S/n	Adsorbent sample	$M_{initial}$ (g)	M_{final} (g)	ΔM (g)	Weight fraction (x) of MEA (%)	CO_2 Adsorption capacity (CO_2/g Adsorbent)
1	C_1-MEA-x	16.31	16.41	0.10	28	0.006
2	C_2-MEA-x	13.15	13.48	0.13	34	0.010
3	C_3-MEA-x	10.38	10.53	0.15	39	0.014
4	C_1-MEA-x+C_3-MEA-x	26.69	26.93	0.24	33	0.009

MEA=Monoethanolamine, ΔM = change in mass, $M_{initial}$ = initial mass, M_{final} = final mass, C_1-MEA-x= First aluminium foam with amine loading, C_2-MEA-x= Second aluminium foam with amine loading, C_3-MEA-x= Third aluminium foam with amine loading

As the amine loading (MEA content) increases from 28% to 39%, the CO_2 adsorption capacity improves significantly due to the increased availability of amine groups, which provide more active sites for CO_2 adsorption. However, there is a trade-off, as higher MEA content may lead to gas flow resistance and pressure drops, resulting from denser surface morphologies (Mustapha *et al.*, 2022; Madgule *et al.*, 2023). While maximising amine loading enhances CO_2 capture, surface

morphology and gas permeability must be optimised to ensure efficiency in larger-scale applications. Overall, higher MEA content boosts CO_2 adsorption, emphasising the need for balance in material design for carbon capture efficiency.

CONCLUSION

Functionalising three aluminium metal foams (C_1, C_2, and C_3) with amine groups (MEA) has significantly improved their CO_2 capture capabilities. Among these, C3-MEA-x demonstrated the highest amine loading (39%), highlighting the importance of the foam's structural characteristics in enhancing amine grafting efficiency. The MEA-functionalised foams show promising potential for gas adsorption applications, with higher amine loadings correlating with increased CO_2 capture efficiency. The study confirmed the successful attachment of amine groups, with nitrogen content increasing as amine loading rose. Despite reduced porosity causing higher pressure drops, the improved adsorption capacity, particularly in C_3-MEA-x, highlights the potential of these foams for gas separation, environmental management and applications. As amine loading increased from 28% (C1-MEA-x) to 39% (C_3-MEA-x), CO_2 adsorption capacity significantly improved due to the greater number of active sites for CO_2 binding.

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