THE MACROPOROUS CERAMIC MATERIALS AS CARBON CAPTURE STORAGE (CCS)

GOH KEAT BENG

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

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This report is submitted in fulfillment of the requirement for the award of Bachelor of Degree of Mechanical Engineering with Honours (Structure & Materials)

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Universiti Teknikal Malaysia Melaka

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DECLARATION

"I hereby declare that the work in this report is my own except for summaries and quotations which have been duly acknowledged."

Signature: ....

Author: GOH KEAT BENG

Date: ....

This project is dedicated to my loving mother who has always giving me moral support during the times I was developing the material and finishing the project. She has never failed to constantly encourage me even when she was busy with her own agenda. I would also like to dedicate this work to my brother for the financial supports he had given to me. Last but not least, I would like express a token of appreciation to my supportive friends who had provided me with useful advises to accomplish the project. Thanks to them for their love and patience they had given to me in achieving my goal.

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ABSTRAK

Pemanasan global merujuk kepada peningkatan purata suhu di atmosfera permukaan bumi. Salah satu punca yang mencetuskan pemanasan global adalah kandungan karbon dioksida (CO_2) yang berlebihan di atmosfera. Maka, objektif projek ini adalah menghasilkan bahan seramik berongga sebagai *carbon capture storage* (CCS) untuk menapis CO_2. Akan tetapi, sifat-sifat seperti ketumpatan dan kekuatan mampatan bahan seramik berongga masih tidak diketahui. Bahan seramik berongga diperbuat daripada campuran komposisi simen, serbuk aluminum, alumina (Al_2O_3), kalsium oksida (CaO), gipsum (kalsium sulfat dihidrat, $CaSO_4.2H_2O$), serbuk silika dan air suling (H_2O) yang sesuai. Komposisi bahan seramik berongga yang berlainan telah dihasilkan iaitu 2*wt*%, 3*wt*% dan 4*wt*% serbuk aluminium. Sifat mekanikal dan struktur keronggaan makro bahan seramik berongga tersebut dianalisis dan dibanding. Sifat-sifat optimum bahan seramik berongga telah ditentukan pada 3*wt*% serbuk aluminium dan menurun secara drastik pada 4*wt*%. Fenomena ini disebabkan oleh tindak balas kimia antara serbuk aluminium dan air suling di mana aluminium oksida yang meningkatkan kekuatan bahan seramik berongga terhasil, walau bagaimanapun pada masa yang sama, kuantiti liang yang tinggi juga terbentuk pada kadar tindak balas yang tinggi antara kedua-dua bahan asas tersebut.

ABSTRACT

Global warming refers to the increase in average temperature of the atmosphere near the earth's surface. One of the main causes that trigger global warming is the excessive content of carbon dioxide (CO_2) in the atmosphere. Therefore, the objective of this project is to produce a porous ceramic material as a carbon capture storage (CCS) to adsorb CO_2. However, the properties such as density and compressive strength of the porous ceramic material are unknown. The porous ceramic material is developed by mixing an appropriate composition of cement, aluminum powder (Al), alumina (Al_2O_3), calcium oxide (CaO), gypsum (calcium sulfate dehydrate, $CaSO_4.2H_2O$), silica powder and deionized (DI) water. Different compositions of porous ceramic were produced at 2wt%, 3wt% and 4wt% of aluminium powder. Their mechanical properties and macro-porosity structural of the porous ceramic material were analyzed and compared. It is determined that the optimal properties of porous ceramic material were found at 3wt% of aluminium powder and degraded drastically at 4wt%. This phenomenon is due to the chemical reaction between the aluminium powder and DI water in which they form aluminium oxide that promotes the strength of the material but at the same time, more pores are created at higher reaction rate between these two fundamental materials.

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LIST OF SYMBOLS

K_{IC}	-	Fracture Toughnessm Mpa.$m^{1/2}$
E	-	Young Modulus, Gpa
σ	-	Compressive Strength, Mpa
P	-	Compressive Load, N
A	-	Cross-Sectional Area, m^2
T	-	Temperature, °C
D	-	Diameter, m
h	-	Height, m
V	-	Volume, m^3
ρ	-	Density, kgm^{-3}

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CHAPTER 1

INTRODUCTION

1.0 INTRODUCTION

Carbon dioxide (CO_2) is a colorless and odorless gas found within the earth's atmosphere. It is a product of combustion and of respiration in which it is exhaled for the exchange of oxygen (O_2) and is also an important gas utilized in the process of photosynthesis in plants. It is also very useful in extinguishing flames. CO_2 is the most important greenhouse gases. It is emitted into the atmosphere whenever organic matter such as fuel is burned. The carbon in the organic matter reacts with air to produce CO_2 and energy (Scottish Carbon Capture & Storage, 2012).

One of the largest sources of CO_2 emission are from fossil fuel powered power stations. According to recent studies, approximately 40% of all CO_2 emission comes from power plants. Three types of polluting power plants are natural gas, coal and oil. Second largest CO_2 contributor is the pollution emitted from cars. Traffic jam is the one of the simplest example to describe the large amount of CO_2 emission into the atmosphere by cars. Longer traffic will cause higher CO_2 emission into the atmosphere as the cars stay longer idly on the road. Third largest pollution comes from truck. It is less in volume compared to cars, but it makes up for a large portion of the earth's pollution with each truck's individual output of pollutants. The difference between cars and trucks is the type of fuel used to run. Trucks and other vehicles that carry large loads use diesel as their standard fuel, which is known to be less clean than gasoline (Christodoulou, G., 2007).

Photosynthesis

$$CO_2 + H_2O + \text{sunlight} \longrightarrow CH_2O + O_2$$

Respiration

$$O_2 + CH_2O \longrightarrow \text{energy} + H_2O + CO_2$$

Combustion

$$O_2 + \text{hydrocarbons} \longrightarrow \text{energy} + H_2O + CO_2$$

(Source: “The Greenhouse Effect and Global Warming”, The Columbia University)

However, excessive CO_2 in atmosphere can lead to undesired phenomenon called global warming. CO_2 contributes as one of the greenhouse gases in the atmosphere that contribute the greenhouse effects around the globe. The largest contributing source of greenhouse gas is the burning of fossil fuels which leads to the emission of CO_2. When sunlight propagates to the earth’s surface, some of the energy is absorbed and provides warmth that sustains life in the earth and most of the rest is radiated back to the atmosphere at a longer wavelength than the sun light. Some of these longer wavelengths are absorbed by the greenhouse gases in the atmosphere before they are lost to space. These greenhouse gases acts like a mirror and reflect some of the heat energy back to the earth. This reflective phenomenon is called the “greenhouse effect” (Time for change – Cause and effect of global warming, 2007).

The phenomenon affects the comfort of human lives as well as raises the average temperature of the earth that results in flooding of low level areas. Therefore, preventive action should be taken to avoid the occurrence of this phenomenon.

Porous ceramic materials can be used as carbon capture storage (CCS) by adsorbing carbon dioxide (CO_2) and carbon monoxide (CO). The initial use of ceramic was originated from the Greek word “keramikos”, meaning fired clay. During the olden days, pores have been avoided to increase crack resistance, but as an increasing number of application that require porous ceramic have emerged in the last decades (Andersson, L., 2011).

The efficiency of adsorbing CO_2 and CO is highly dependent of the material composition used to form the porous ceramic material. Aluminum powder with addictive can absorb CO_2 and CO at normal temperatures. Alumina will be formed by the reaction between aluminum and oxygen at high temperatures and thus the porous ceramic material can be used at high temperatures since the melting point of alumina product is extremely high. Calcium oxide (CaO) can be utilized to absorb CO_2 at high temperature (600°C - 700°C) through carbonation reaction (Yin, J, et al. 2012).

1.1 PROBLEM STATEMENT

Excessive carbon dioxide (CO_2) in the atmosphere can lead to global warming through increased greenhouse effect. Thus, macro porous ceramic material is introduced to filter the CO_2 emitted by power plants and vehicles. It has a high potential in absorbing CO_2 in a wide range of temperature and it is able to withstand corrosive environment (Yin, J, et al. 2012). However, the sustainability of the ceramic material to endure physical and mechanical failures in term of stresses is still unidentified. Pores are also necessary for the ceramic material to absorb CO_2 effectively. Therefore, the purpose of this project is to determine the optimum properties in between the mechanical properties and microstructure of the macro porous ceramic material for its application in CO_2 absorption.

1.2 OBJECTIVES

The objectives in this project are to research an alternative solution to solve the phenomenon of global warming. Therefore, the three main objectives of the project are:

1. To produce a porous ceramic material.
2. To test and determine the mechanical properties of porous ceramic product.
3. To analyze a macro and micro structure of porous ceramic material.

1.3 SCOPE OF RESEARCH

This research is to establish suitable characterization methods for the macro porous aluminum materials. It is conducted to study how macro and micro-porosity can be combined as ceramic bulk materials and how these materials can be used as hierarchically structure absorbents for carbon dioxide (CO_2) separation.

CHAPTER 2

LITERATURE REVIEW

2.0 LITERATURE REVIEW

This chapter describes the research conducted via sources from journals which includes a brief introduction of porous ceramics, fabricating process of macroporous ceramic material, properties of the ceramic and effectiveness of the material in CO_2 absorption application as well as appropriate mixture of raw materials to obtain the optimum properties of the ceramic material. There are three distinctive techniques in fabricating the porous ceramics in which they are replica method, sacrificial template and direct foaming. The strength and the efficiency of the porous ceramic material in CO_2 absorption are highly dependent on its microstructure. Pores are required in CO_2 absorption but it also determines the strength of the ceramic material. Therefore, the mechanical properties of the porous ceramic are to be experimented thoroughly to establish a favourable relationship in between the porosity and the density in order to obtain the optimum strength of the porous ceramic material.

2.1 POROUS CERAMICS

Porous ceramics are recently being studied for its application in various industries such as filters, high-temperature thermal insulation, supports for catalysts and bone substitutes (Khattab, R.M. et. al. 2012). The application of porous ceramics depends on its characteristics and permeability. It usually has low density due to the pores distribution in the structure of ceramics which contributes to its high permeability. There are two types of pores in porous ceramic material. One of them is reticulate or open-celled structure, where the structure consists of interconnected voids surrounded by a web of ceramic. The other one is called foam or closed-cell structure, where the voids are closed and there no is linkage within the continuous ceramic matrix (Surabhi, S., 2012). According to IUPAC, ceramics can be divided into three categories based on the pore sizes. They are micro, meso and macro. The size of pores for microporous ceramics is less than 2 nm, mesoporous ceramics within the range of 2 nm to 50 nm and macroporous ceramics with pores greater than 50 nm (Pekor, C.M., 2003).

One of the basic materials in forming porous ceramics is alumina (Al_2O_3). Alumina is generally chosen as a basic material because it possesses good mechanical and thermal properties, as well as inert to most chemical attacks. Porous alumina materials are used in various forms. For example, polymeric foams are used for packing and porous ceramics are used in water purification (Surabhi, S., 2012).

Traditionally, pores are avoided in ceramic materials because they reduce the material's strength due to their brittleness. However, in the past few decades, applications that require porous ceramics have surfaced where aggressive environment such as corrosive and high temperatures which induce excessive wear are involved (Surabhi, S., 2012). Porous ceramics which contain alumina are usually used in situations that engage with harsh environments due to its high stability to acidic or alkaline conditions. Its inert nature provides a high corrosion resistance; enabling the porous ceramic materials in application that involves chemical reactions. Alumina based porous ceramics also possesses high melting point. Therefore, it has not only relatively good mechanical properties and chemical stability; it is also applicable in mechanism that involves extreme temperature such as high-temperature thermal insulation, filtration of gases from vehicle exhausts and filtration in hot corrosive gases in various industrial applications (Surabhi, S., 2012).

2.2 THE MECHANICAL PROPERTIES OF MACROPOROUS CERAMIC MATERIAL

Compared to metal and polymer foams, macroporous ceramics are lightweight materials with high specific strength. In the ceramic materials, the components can be classified into struts and vertices. Struts are the walls separating the pore space either the pores are interconnected or isolated. Vertices are the spots where the struts join (Andersson, L., 2011).

According to Gaiye Li, Yiqun Fan, Yuan Zheng and Yuping Wu, 2010, the fracture toughness, K_{IC} for alumina ceramics is generally within the range of 0.3 – 0.5 $Mpa.m^{1/2}$. It is dependent of the contents of pores or pore distribution per unit area. Therefore, addictives such as aluminum powder or Yttria-Stabilized Zirconia powder (YSZ) with suitable portions can be added to improve the fracture toughness. By directed metal oxidation method, Al/Al_2O_3 exhibits a fracture toughness of 9.5 $Mpa.m^{1/2}$. Fracture toughness of 5.8 $Mpa.m^{1/2}$ and bending strength of 760 Mpa are shown by Al/Al_2O_3 through gas pressure metal infiltration method.

According to Linnea Andersson, 2011, the strength of macroporous ceramic materials increases with increasing density. This statement can be represented by the models developed by Gibson and Ashby, 1988:

$$\frac{E}{E_s} = C\left(\frac{\rho}{\rho_s}\right)^n$$

This experimental model indicates that the Young Modulus E of a macroporous material is related to the apparent density. E_s denotes the modulus of the solid material, C denotes a constant and n represents an empirically determined exponent. The models are capable to predict the mechanical properties and behavior of macroporous materials (Andersson, L., 2011).

2.3 FABRICATION OF MACROPOROUS CERAMICS

Porous ceramics which are usually more durable in harsh environments have triggered a new challenge to several industries in the development of porous ceramic materials. As the demand for porous ceramics in industrial applications keep emerging, several technologies have developed to fabricate these porous ceramics. It is critical to identify which method to be used to fabricate porous ceramic materials as their properties and pore characteristics are generally dependent of fabrication techniques.

There are three different fabrication methods for producing highly porous macroporous ceramics which are the replica technique, the sacrificial template and direct foaming methods (Andersson, L.,2011).

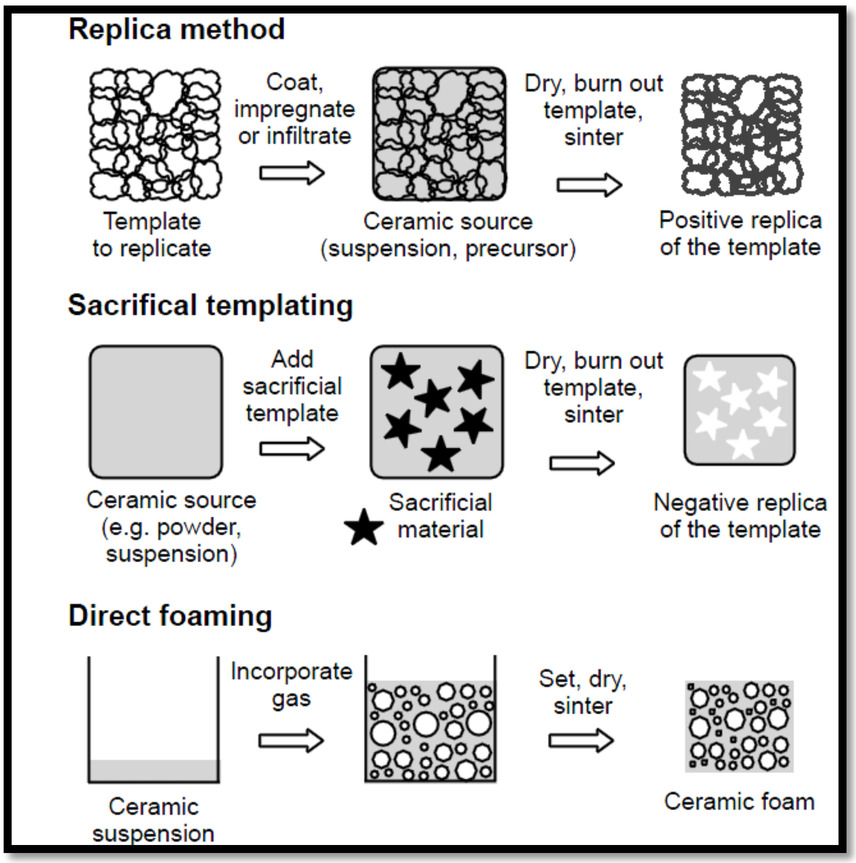

Figure 2.1: Three Possible Techniques for Making Macro Porous Materials: The Replica, The Sacrificial Template and The Direct Forming.

(Source: Andersson, L., 2011)