UNIVERSITI PUTRA MALAYSIA

MODIFIED CENOSPHERES AS NON-SACRIFICIAL PORE-FORMING AGENT FOR DEVELOPMENT OF POROUS MULLITE CERAMICS ENTIRELY FROM INDUSTRIAL WASTES

CHOO THYE FOO

ITMA 2021 7

MODIFIED CENOSPHERES AS NON-SACRIFICIAL PORE-FORMING AGENT FOR DEVELOPMENT OF POROUS MULLITE CERAMICS ENTIRELY FROM INDUSTRIAL WASTES

By

CHOO THYE FOO

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

August 2021

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

MODIFIED CENOSPHERES AS NON-SACRIFICIAL PORE-FORMING AGENT FOR DEVELOPMENT OF POROUS MULLITE CERAMICS ENTIRELY FROM INDUSTRIAL WASTES

By

CHOO THYE FOO

August 2021

Chairman : Associate Professor Mohamad Amran bin Mohd Salleh, PhD
Institute : Advanced Technology

Mullite is a widely used ceramic because it exhibits some advantageous properties such as thermal shock resistance, chemical resistance, creep resistance, high hot strength and low coefficient of thermal expansion. Driven by the need for low-cost and environmentally friendly alternatives, extensive research on the utilization of low-cost materials to produce mullite ceramics is crucial. In this study, mullite ceramics were produced entirely from aluminum dross (AD) and coal fly ash (CFA) industrial wastes. Both wastes were mixed together in different weight ratio, subsequently compacted and sintered. The effects of the sintering temperature, acid leaching and Al_2O_3/SiO_2 ratio on the chemical, physical, thermal expansion properties of the samples were characterized in detail. The results showed that appropriate mixing ratio and acid leaching had positive effects on the mineralogy, crystallinity, and macromorphology of sintered samples. At sintering temperature of 1500 °C, high mullite content ceramics with good crystallinity were produced. The resultant ceramics exhibited excellent thermal expansion properties with coefficient of thermal expansion (CTE) values ranging from 4.0 to 5.9 $\times 10^{-6}$ °C^{-1}. Modified cenospheres were used as non-sacrificial pore-forming agent to produce porous mullite ceramics. The results showed that addition of modified cenospheres leads to the increment of both total porosity and closed porosity, with the reduction of open porosity. Addition of 40 wt% of modified cenospheres to the mullite precursor, the resultant porous mullite ceramic has a total porosity of 50.2%, thermal conductivity of 1.28 $Wm^{-1}K^{-1}$, linear shrinkage of 4%, and biaxial flexural strength of 45.9 MPa. The mullite precursor was also used to produce high-temperature porous mullite washcoat. Results showed that the precursor transformed to a hierarchical porous microstructure assembled by large interlocked acicular mullite crystals. The specific surface area of the washcoat was 4.85 m^2g^{-1}, which comparable to the other high-temperature washcoats.

This study offers the potential of using these industrial wastes as a sustainable alternative raw material in the development of mullite ceramics.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

CENOSPHERES TERUBAHSUAI SEBAGAI AGEN PEMBENTUKAN LIANG TANPA LESAP UNTUK PEMBANGUNAN SERAMIK MULIT BERLIANG DARIPADA SISA-SISA INDUSTRI SEPENUHNYA

Oleh

CHOO THYE FOO

Ogos 2021

Pengerusi : Profesor Madya Mohamad Amran bin Mohd Salleh, PhD
Institut : Teknologi Maju

Mulit adalah seramik yang digunakan secara meluas kerana ia mempunyai ciri-ciri kelebihan seperti ketahanan kejutan terma, ketahanan kimia, ketahanan rayapan, kekuatan panas yang tinggi dan pekali pengembangan haba yang rendah. Didorong oleh permintaan bahan alternatif yang murah dan mesra alam, penyelidikan yang mendalam mengenai penggunaan bahan kos rendah untuk penghasilan mulit adalah sangat penting. Dalam kajian ini, Seramik mulit dihasilkan sepenuhya daripada sisa-sisa industri seperti serdak aluminum dan abu terbang arang batu. Kedua-dua sisa ini dicampurkan dengan nisbah keberatan yang berbeza, kemudian dipadat dan disinter. Kesan-kesan suhu sinter, rawatan asid dan nisbah Al_2O_3/SiO_2 terhadap sifat kimia, fizikal, dan pengembangan haba sampel dikaji dengan terperinci. Hasil kajian menunjukkan bahawa nisbah campuran yang sesuai dan rawatan asid memberi kesan positif terhadap mineralogi, kehabluran, dan makromorfologi sampel yang disinter. Pada suhu sinter 1500 °C, seramik berkandungan mulit yang tinggi dengan tahap kehabluran yang baik telah dihasilkan. Seramik tersebut mempamerkan sifat pengembangan haba yang sangat baik dengan nilai pekali pengembangan haba dari 4.0 hingga 5.9 $\times10^{-6}$ °C^{-1}. Cenospheres terubahsuai telah digunakan sebagai agen pembentukan liang tanpa lesap untuk menghasilkan seramik mulit berliang. Hasil kajian menunjukkan bahawa penambahan cenospheres terubahsuai meningkatkan jumlah liang dan liang tertutup, di samping itu mengurangkan liang terbuka. Penambahan 40 wt% cenospheres terubahsuai menghasilkan seramik mulit berliang yang mempunyai jumlah liang sebanyak 50.2%, kekonduksian haba sebanyak 1.28 $Wm^{-1}K^{-1}$, pengecutan linear sebanyak 4%, dan kekuatan lenturan biaksial sebanyak 45.9 MPa. Prekursor mulit juga telah digunakan untuk menghasilkan pembawa mangkin mulit berliang suhu-tinggi. Hasil kajian menunjukkan bahawa prekursor bertukar kepada satu mikrostruktur berliang hierarki yang dibentukkan oleh kristal mulit asikular besar yang berpautan. Keluasan permukaan spesifik pembawa

mangkin mulit adalah 4.85 m^2g^{-1}, dimana setanding dengan pembawa mangkin suhu tinggi yang lain. Kajian ini menawarkan potensi menggunakan sisa-sisa industri ini sebagai bahan mentah alternatif yang mampan dalam penghasilan seramik mulit.

ACKNOWLEDGEMENTS

I would like to express my greatest appreciation to my supervisor, Associate Professor Dr. Mohamad Amran Bin Mohd Salleh and co-supervisor Dr. Kok Kuan Ying, Associate Professor Dr. Khamirul Amin Matori, Professor Dr. Suraya Abdul Rashid for their generous guidance, advice and motivation throughout this research.

A special thank dedicated to my beloved wife and parents, for their continuing morale supports throughout my studies. My sincere appreciation also extends to all my friends, the laboratory personnel, those who were directly or indirectly involved in the process of producing this research report, for their generous assistance, useful views and tips. Finally, I would like to thank the Malaysia government for awarding me a Public Services Department (JPA) scholarship for my PhD study.

Without their support and contribution, this research project would not have been possible.

This thesis was submitted to the Senate of the Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

Mohamad Amran bin Mohd Salleh, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Khamirul Amin bin Matori, PhD
Associate Professor
Faculty of Science
Universiti Putra Malaysia
(Member)

Suraya binti Abdul Rashid, PhD
Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Kok Kuan Ying, PhD
Research officer
Malaysian Nuclear Agency
Malaysia
(Member)

ZALILAH MOHD SHARIFF, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 11 November 2021

Declaration by graduate student

I hereby confirm that:

- this thesis is my original work;
- quotations, illustrations and citations have been duly referenced;
- this thesis has not been submitted previously or concurrently for any other degree at any institutions;
- intellectual property from the thesis and copyright of thesis are fully-owned by Universiti Putra Malaysia, as according to the Universiti Putra Malaysia (Research) Rules 2012;
- written permission must be obtained from supervisor and the office of Deputy Vice-Chancellor (Research and innovation) before thesis is published (in the form of written, printed or in electronic form) including books, journals, modules, proceedings, popular writings, seminar papers, manuscripts, posters, reports, lecture notes, learning modules or any other materials as stated in the Universiti Putra Malaysia (Research) Rules 2012;
- there is no plagiarism or data falsification/fabrication in the thesis, and scholarly integrity is upheld as according to the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) and the Universiti Putra Malaysia (Research) Rules 2012. The thesis has undergone plagiarism detection software

Signature: ________________________ Date:_____________

Name and Matric No: Choo Thye Foo, GS52067

Declaration by Members of Supervisory Committee

This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) were adhered to.

Signature: ______________________

Name of Chairman of Supervisory Committee: Associate Professor Dr. Mohamad Amran bin Mohd Salleh

Signature: ______________________

Name of Member of Supervisory Committee: Associate Professor Dr. Khamirul bin Amin Matori

Signature: ______________________

Name of Member of Supervisory Committee: Professor Dr. Suraya binti Abdul Rashid

Signature: ______________________

Name of Member of Supervisory Committee: Dr. Kok Kuan Ying

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

LIST OF ABBREVIATIONS

EDXRF	Energy dispersive X-ray fluorescence
XRD	X-ray diffraction
FESEM	Field emission scanning electron microscope
EDS	Energy dispersive spectroscopy
CTE	Coefficient of thermal expansion
TG-DSC	thermogravimetry and differential scanning calorimetry analysis
BET	Brunauer-Emmer-Teller
BJH	Barrett-Joyner-Halenda
rpm	Revolutions per minute
MPa	Mega Pascal
CFA	Coal fly ash
AD	Aluminum dross
MP	Mullite precursor
P/P_0	Relative pressure
ICDD	International Centre for Diffraction Data
d50	average particle size
IUPAC	International Union of Pure and Applied Chemistry

CHAPTER 1

INTRODUCTION

1.1 Brief introduction

Mullite ($3Al_2O_3{\cdot}2SiO_2$) is the chemically stable intermediate phase in the silica – alumina system. It is a widely used ceramic because it exhibits some advantageous properties such as thermal shock resistance, chemical attack resistance, creep resistance, high hot strength and low coefficient of thermal expansion. Driven by the need for low-cost and environmentally friendly alternatives, many research efforts have used a variety of industrial wastes as starting materials to produce mullite ceramics.

One of the industrial wastes being used as starting materials to produce mullite ceramics is coal fly ash (CFA). Most of the past efforts on CFA utilization in mullite production have been focused on the preparation of mullite ceramic and its composites with addition of other aluminum sources such as alumina, aluminum hydroxide, aluminum sulfate and bauxite. This is because the SiO_2 content in CFA is often excessive for the amount required for the preparation of mullite. Furthermore, excessive SiO_2 associated with impurities can lead to a sample deformation or meltdown in high-temperature sintering. Generally, percentage of mullite in CFA can be increased by introducing additional aluminum source before mullitization phase transformation takes place; this aluminum source will then combine with the remaining free SiO_2 in CFA to form additional mullite. Although all these processes from the previous studies are feasible, they utilized CFA as an alternative silica source, but the aluminum source they utilized is not a waste, which defeats the purpose of using industrial waste in the first place. Aluminum Dross (AD) is a waste product, which produced from secondary aluminum refining. This waste product has high content of Al_2O_3. This makes AD a good candidate waste material to mix with CFA to produce mullite.

Past and current development of porous mullite have been focused on producing mullite ceramics with high permeability, in other words, the majority of the pores are technically open, functioning as small channels. The open pores and pore channels formation are related to pyrolysis; burnout; sublimation of sacrificial pore-forming agent and binder. Generally, close pores are difficult to form and control using these methods. A so-called non-sacrificial pore-forming agent is different from the traditional sacrificial pore-forming agent. This type of pore-forming agent is based on its ability to increase the porosity of the matrix by its internal hollow volumes, and with little or no disintegration in the process. Therefore, non-sacrificial pore-forming agent is more suitable to produce porous mullite ceramic with majority closed pores. Coal fly ash cenospheres are aluminosilicate hollow spheres with high silica and alumina content. Cenospheres have been utilized as non-sacrificial pore-forming agent in some low-temperature applications. However, it has not yet been successfully proven to be used in high-temperature applications. Therefore, it is crucial to understand the thermal behaviors of the cenospheres at high temperatures, so that it can be used as a non-sacrificial pore-forming agent for the porous mullite ceramics fabrication.

Monolith washcoat is the crucial component of a catalyst support. It is where the catalytic reactions take place, as the main function of the washcoat is to provide high contact surface area between the catalyst and reacting gases for high reaction rates. Additionally, the washcoat has to be thermally stable at working temperatures. Mullite appears to be promising candidate for this high-temperature (>1000 °C) washcoat application. Therefore, it is also important to investigate the feasibility of using aluminum dross and coal fly ash derived mullite precursor in the production of mullite washcoat.

1.2 Problem statements

Mullite is a promising advanced ceramic material. It can be produced from a variety of raw materials, namely chemicals, natural minerals, industrial wastes, or a combination of them. Over the years, manufacturing cost reduction efforts have gained much attention. The utilization of low-cost raw materials for ceramics production has become more desirable. Although some studies concerning about the use of low-cost materials to produce mullite ceramic had been published. But the utilization of 100% wastes to produce high-content mullite ceramic is still unachievable.

Coal fly ash (CFA) is a by-product in coal-fired powerplant. CFA is utilized in industry as a substitute for fine aggregates in cement and concrete, in bricks and ceramic tiles, as filler in plastics and paints. But the utilization rate of the fly ash is rather low. In general, CFA has pozzolanic properties and its major mineral phases are silica and alumina in the form of quartz and mullite. Aluminum Dross (AD) is also a waste product, it produced from secondary aluminum refining. Currently, AD is processed in rotary kilns to recover the Al, and the resultant salt cake is sent to landfills. Although it is sealed to prevent from leaching, the potential for leaching still exists. Illegal dumping of this toxic waste can lead to serious environmental problem which could harm human health and the environment due to the fluorides and other salts contents in the salt cake. Owing to the high content of useful minerals in CFA and AD, it is economically viable to recover these minerals for useful industrial applications. Furthermore, energy consumed in the waste treatment can be saved if the wastes could be developed as a new material.

Most of the porous mullite ceramics have high permeability, in other words, the majority of the pores are technically open, functioning as smallb channels. This type of porous ceramics is not suitable for refractory. The penetration of hot flowing gases and liquid melt in the pores may cause refractory failure, and toxic gas at high pressure that leak through the pores may cause safety hazard. Therefore, the development of porous mullite ceramics with less open pores is crucial for refractory.

1.3 Scope of study

In first part of this study, coal fly ash (CFA) and aluminum dross (AD) were investigated as the sole raw materials in the production of mullite-based ceramics. Both of the industrial wastes were mixed together in different weight ratio, subsequently compacted and sintered. The effects of the sintering temperature, acid leaching and Al_2O_3/SiO_2 ratio on the chemical, physical, thermal expansion properties of the samples were characterized in detail. The chemical composition was determined by energy dispersive X-ray fluorescence (EDXRF) using a Shimadzu EDX-7000. X-ray diffraction (XRD) pattern at room temperature for the sample was recorded by using PANalytical X'Pert PRO using monochromated CuKα radiation (λ = 1.54184 Å) and phase composition was analyzed by Rietveld refinement method. The evaluation of relative degree of crystallinity of the samples was estimated from the measured X-ray intensity. The microstructure was characterized using a GeminiSEM 500 FESEM (Zeiss, Germany) equipped with an X-Max EDS detector (Oxford Instruments, UK). A Netzsch DIL 402C Dilatometer was used to measure linear thermal expansion of the sintered samples from room temperature to 1000 *°C.*

In second part of the study, the influence of temperature on morphology, phase transformations and thermal expansions of coal fly ash cenospheres was investigated. The cenospheres were extracted from coal fly ash and heat-treated at 800, 1000, 1200 and 1400 °C for 2 hours. The cenospheres and heat-treated cenospheres (1000, 1200 and 1400 °C) were characterized by X-ray diffraction using PANalytical X'Pert PRO. The cenospheres were also characterized by a STA-449-F3 Jupiter simultaneous thermal analyzer (Netzsch, Germany) for their temperature-dependent phase transitions. The cenospheres and heat-treated cenospheres (1000, 1200 and 1400 °C) were characterized using a GeminiSEM 500 FESEM (Zeiss, Germany) equipped with an X-Max EDS detector (Oxford Instruments, UK). The differences between particle morphology, shape and size were analyzed. The Al_2O_3/SiO_2 ratio of mullite crystallites was computed based on the EDS results. A Netzsch DIL 402C Dilatometer was used to measure the linear thermal expansion of the powder samples in an alumina sample container from 100 to 1000 °C at a heating rate of 5 °C/min. The length change was recorded with a dense α-alumina as reference sample.

In third part of the study, porous mullite ceramics were synthesized using the mullite precursor produced from the first part of the study together with modified cenospheres as a non-sacrificial pore-forming agent. In this part of the study, the effects of surface modification on cenospheres and the performance of the resultant porous mullite ceramics will be investigated. The microstructures of the samples were characterized using a Zeiss GeminiSEM 500 field emission scanning electron microscope (FESEM). Chemical composition was determined by energy dispersive X-ray fluorescence (EDXRF) using a Shimadzu EDX-7000. X-ray diffraction (XRD) patterns were recorded by using PANalytical X'Pert PRO using monochromated CuKα radiation (λ = 1.54184 Å) and phase composition were analyzed by Rietveld refinement method. The degree of crystallinity was estimated from the measured X-ray intensity. Thermal conductivity was measured at room temperature using Hot Disk TPS 2500S thermal conductivity analyzer via transient plane source method.

In fourth and last part of the study, the feasibility of the aluminum dross and coal fly ash derived mullite precursor in the production of mullite washcoat was investigated. The precursor was made into slurry using deionized water and dip coated on flat alumina substrates and fired at 1200 °C and 1500 °C for 4 hours. The chemical composition of the starting materials was determined by energy dispersive X-ray fluorescence (EDXRF) using a Shimadzu EDX-7000. Particle size distributions of the powders were measured with the aid of a laser particle size analyzer (Microtrac X100). Zeiss GeminiSEM 500 FESEM was used for the study of the morphology of the starting mullite precursor and the sintered mullite washcoat on alumina substrates. The X-ray diffraction (XRD) pattern at room temperature for the samples were recorded by using PANalytical X'Pert PRO using monochromated CuKα radiation (λ = 1.54184 Å), and the phase composition was analyzed by Rietveld refinement method. N_2 physical adsorption-desorption isotherm of the washcoat was obtained with a surface area analyzer (Quantachrome Autosorb-1-C) at 77 K.

1.4 Objectives of Study

This study is conducted to accomplish some predefined objectives. These objectives are:

I. To synthesize and characterize mullite ceramics developed from coal fly ash (CFA) and aluminum dross (AD), and investigate the effects of the sintering temperature, acid leaching and Al_2O_3/SiO_2 ratio on the chemical, physical, thermal expansion properties of the samples.

II. To investigate the morphology, phase transformations and thermal expansions of the cenospheres at high temperatures, and assess the potential of cenospheres as a non-sacrificial pore-forming agent for porous ceramic fabrication.

III. To synthesize and characterize porous mullite ceramics using the waste derived mullite precursor and modified cenospheres as a non-sacrificial pore-forming agent, and investigate the effects of cenospheres surface modification on the pore characteristic and thermal conductivity of the resultant porous mullite ceramics.

IV. To synthesize mullite washcoat using the waste derived mullite precursor, and characterize the surface properties and pore size distribution of the mullite washcoat.

REFERENCES

Agrafiotis, C and Tsetsekou, A. (2000). The effect of powder characteristics on washcoat quality. Part I: Alumina washcoats, *Journal of the European Ceramic Society* 20: 815–824.

Akpinar, S., Kusoglu, I.M., Ertugrul, O. and Onel, K. (2012). In situ mullite foam fabrication using microwave energy, *Journal of the European Ceramic Society* 32: 843–848.

Angel, R.J. and Prewitt, C.T. (1986). Crystal Structure of Mullite: A Re-examination of the Average Structure, *American Mineralogist* 71: 1476-1482.

Anggono, J. (2005). Mullite Ceramics Its Properties, Structure and Synthesis. *Jurnal Teknik Mesin*, 7: 1-10

Argyle, M.D. and Bartholomew, C.H. (2015). Heterogeneous Catalyst Deactivation and Regeneration: A Review. *Catalysts* 5: 145-269.

Aripin, H., Mitsudo, S., Prima, E.S., Sudiana, I.N., Kikuchi, H., Sano, S. and Sabchevski, S. (2015). Crystalline mullite formation from mixtures of alumina and a novel material - Silica xerogel converted from sago waste ash. *Ceramics International* 41: 6488–6497.

Asl, M.S., Kakroudi, M.G., Kondolaji, R.A. and Nasiri, H. (2015). Influence of graphite nano-flakes on densification and mechanical properties of hot-pressed ZrB_2-SiC composite, *Ceramics International* 41: 5843-5851.

Aziz, S.B., Marf, A.S., Dannoun, E.M.A., Brza, M.A., Abdullah, R.M. (2020). The study of the degree of crystallinity, electrical equivalent circuit, and dielectric properties of polyvinyl alcohol (PVA)-based biopolymer electrolytes. *Polymers 12*: 2184.

Bagheri, S., Muhd Julkapli, N. and Bee Abd Hamid, S. (2014). Titanium dioxide as a catalyst support in heterogeneous catalysis. *The Scientific World Journal* 2014: 727496.

Bai, J. (2010). Fabrication and properties of porous mullite ceramics from calcined carbonaceous kaolin and α-Al_2O_3. *Ceramics International* 36: 673–678.

Balakrishnan, M., Batra, V.S., Hargreaves, J.S.J. and Pulford, I.D. (2011). Waste materials - catalytic opportunities: an overview of the application of large scale waste materials as resources for catalytic applications. *Green Chemistry* 13: 16-24.

Barea, R., Osendi, M.I., Miranzo, P. and Ferreira, J.M.F. (2005). Fabrication of highly porous mullite materials. *Journal of the American Ceramic Society* 88: 777–779.

Barrett, E. P., Joyner, L. G., Halenda, P. R. (1951). The determination of pore volume and area distributions in porous substances. I. Computations from nitrogen isotherms. *Journal of the American Ceramic Society* 73: 373–380.

Belrhiti, Y., Pop, O., Germaneau, A., Doumalin, P., Dupré, J.C., Huger, M. and Chotard, T. (2016). Refinement of digital image correlation technique to investigate the fracture behaviour of refractory materials. *IOP Conf. Series: Materials Science and Engineering* 119: 012010.

Benítez-Guerrero, M., Pérez-Maqueda, L.A., Sánchez-Jiménez, P.E., Pascual-Cosp, J. (2014). Characterization of thermally stable gamma alumina fibres biomimicking sisal. *Microporous and Mesoporous Materials*, 185: 167-178.

Bettermann, P. and Liebau, F. (1975). The transformation of amorphous silica to crystalline silica under hydrothermal conditions. *Contributions to Mineralogy and Petrology* 53: 25-36.

Bibby, D.M. (1977). Composition and variation of pulverized fuel ash obtained from the combustion of sub-bituminous coals, New Zealand. *Fuel* 56: 427-431.

Bird, R.B., Stewart, W.E., Lightfoot, E.N. (1960). *Transport Phenomena.* New York, USA: John Wiley and Sons, Inc.

Blissett, R. and Rowson, N. (2012). A review of the multi-component utilisation of coal fly ash. *Fuel* 97: 1-23.

Brasileiro, M.I., Rodrigues, A.W.B., Menezes, R.R., Neves, G.A. and Santana, L.N.L. (2012). The Kaolin Residue and Its Use for Production of Mullite Bodies. In Ghenai, C. (Ed.) *Sustainable Development - Energy, Engineering and Technologies - Manufacturing and Environment* (pp. 117-142) Rijeka: Intech.

Bressiani, J.C., V. Izhevskyi, V. and Bressiani, H.A. (1999). Development of the Microstructure of the Silicon Nitride Based Ceramics. *Materials Research* 2: 165-172.

Cao, J., Dong, X., Li, L., Dong, Y. and Hampshire, S. (2014). Recycling of waste fly ash for production of porous mullite ceramic membrane supports with increased porosity. *Journal of the European Ceramic Society* 34: 3181–3194.

Casas-Luna, M., Torres-Rodríguez, J.A., Valdés-Martínez, O.U., Obradovic, N., Slámecka, K., Maca, K., Kaiser, J., Montúfar, E.B., Celko, L. (2020). Robocasting of controlled porous $CaSiO_3$–SiO_2 structures: Architecture – Strength relationship and material catalytic behavior, *Ceramics International* 46: 8853–8861.

Catarino, L., Sousa, J., Martins, I.M., Vieira, M.T. and Oliveira, M.M. (2003). Ceramic products obtained from rock wastes. *Journal of Materials Processing Technology* 144: 843–845.

Cavillon, M., Dragic, P.D. and Ballato, J. (2017). Additivity of the coefficient of thermal expansion in silicate optical fibers. *Optics Letters* 42: 3650-3653.

Chen, A., Li, M., Wu, J., Cheng, L., Liu, R., Shi, Y. and Li, C. (2019). Enhancement mechanism of mechanical performance of highly porous mullite ceramics with bimodal pore structures prepared by selective laser sintering. *Journal of Alloys and Compounds* 776: 486-494.

Chen, A.N., Li, M., Xu, J., Lou, C.H., Wu, J.M., Chen, L.J., Shi, Y.S. and Li, C.H. (2018). High porosity mullite ceramic foams prepared by selective laser sintering using fly ash hollow spheres as raw materials, *Journal of the European Ceramic Society* 38: 4553-4559.

Chen, C.Y., Lan, G.S., Tuan, W.H. (2000). Preparation of mullite by the reaction sintering of kaolinite and alumina, *Journal of the European Ceramic Society* 20: 2519–2525.

Choo, T.F., Mahmood, C.S. and Mohd Salleh, M.A. (2011). The study of aluminum loss and consequent phase transformation in heat-treated acid-leached kaolin. *Materials Characterization* 62: 373-377.

Choo, T.F., Murshidi, J.A., Saidin, N.U., Paulus, W. and Abdullah, Y. (2017). Production of Mullite Ceramic Bodies from Kaolin Processing Waste and Aluminum Hydroxide. *Materials Science Forum* 888: 81–85.

Cui, K., Zhang, Y., Fu, T., Wang, J., Zhang, X. (2020). Toughening Mechanism of Mullite Matrix Composites: A Review. *Coatings 10*: 672.

Deepthi, M.V., Sharma, M., Sailaja, R.R.N., Anantha, P., Sampathkumaran, P. and Seetharamu, S. (2010). Mechanical and thermal characteristics of high density polyethylene - fly ash Cenospheres composites. *Materials & Design* 31: 2051-2060.

Deng, X., Wang, J., Liu, J., Zhang, H., Li, F., Duan, H., Lu, L., Huang, Z., Zhao, W., Zhang, S. (2015). Preparation and characterization of porous mullite ceramics via foam gelcasting. *Ceramics International* 41: 9009-9017.

Deng, X.G., Wang, J.K., Zhang, H.J., Liu, J.H., Zhao, W.G., Huang, Z. and Zhang, S.W. (2016). Effects of firing temperature on the microstructures and properties of porous mullite ceramics prepared by foam-gelcasting. *Advances in Applied Ceramics* 32: 204-209.

Deng, Z.Y., Fukasawa, T., Ando, M. (2001) High-surface-area alumina ceramics fabricated by the decomposition of $Al(OH)_3$, *Journal of the American Ceramic Society* 84: 485–491.

Doddamani, M., Mathapati, M. and Ramesh, M.R. (2018). Microstructure and tribological behavior of plasma sprayed NiCrAlY/WC-Co/cenosphere/solid lubricants composite coatings. *Surface and Coatings Technology*, 354: 92-100.

Dong, Y., Diwu, J., Feng, X., Feng, X., Liu, X. and Meng, G. (2008). Phase evolution and sintering characteristics of porous mullite ceramics produced from the flyash-$Al(OH)_3$ coating powders. *Journal of Alloys and Compounds* 460: 651–657.

Dong, Y., Feng, X., Feng, X., Ding, Y., Liu, X. and Meng, G. (2008). Preparation of low-cost mullite ceramics from natural bauxite and industrial waste fly ash. *Journal of Alloys and Compounds* 460: 599-606.

Dong, Y., Hampshire, S., Zhou, J., Ji, Z., Wang, J. and Meng, G. (2011). Sintering and characterization of flyash-based mullite with MgO addition. *Journal of the European Ceramic Society* 31: 687–695.

Dong, Y., Hampshire, S., Zhou, J., Lin, B., Ji, Z., Zhang, X. and Meng, G. (2010). Recycling of fly ash for preparing porous mullite membrane supports with titania addition. *Journal of Hazardous Materials* 180: 173-180.

Dong, Y., Zhou, J., Lin, B., Wang, Y., Wang, S., Miao, L., Lang, Y., Liu, X. and Meng, G. (2009). Reaction-sintered porous mineral-based mullite ceramic membrane supports made from recycled materials. *Journal of Hazardous Materials* 172: 180–186.

Dos Santos, E.J., Zagonel, G.F., Herrmann, A.B., Fantin, E.B., Sturgeon, R.E. (2018). Determination of aluminium phosphide (AlP) in fumigants by ICP OES. *Analytical Methods* 10: 5047-5050

Duxson, P., Fernandez-Jimenez, A., Provis, J.L., Lukey, G.C., Palomo, A. and Van Deventer, J.S.J. (2007). Geopolymer technology: the current state of the art. *Journal of Materials Science* 42: 2917-2933.

Energy Commission (EC), (2015). *Malaysia Energy Statistics Handbook*. Malaysia: Energy Commission.

Farenholtz, W.G., Smith, D.M., Cesarano III, J. (1993). Effect of precursor particle size on the densification and crystallization behavior of mullite, *Journal of the American Ceramic Society* 76: 433–437.

Feng, F., Jang, B., Park, J.Y. and Lee, K.S. (2016). Effect of Yb_2SiO_5 addition on the physical and mechanical properties of sintered mullite ceramic as an environmental barrier coating material. *Ceramics International* 42: 15203-15208.

Fischer, R.X., Andrea, G.K., Birkenstock, J., Schneider, H. (2012) Mullite and mullite-type crystal structures. *International Journal of Materials Research* 103: 402-407.

Fluegel, A., Earl, D.A., Varshneya A.K., and Seward III, T.P. (2008). Density and thermal expansion calculation of silicate glass melts from 1000°C to 1400°C. *Physics and Chemistry of Glasses: European Journal of Glass Science and Technology Part B* 49: 245–257.

Fomenko, E.V., Anshits, N.N., Solovyov, L.A., Mikhaylova, O.A. and Anshits, A.G. (2013). Composition and Morphology of Fly Ash Cenospheres Produced from the Combustion of Kuznetsk Coal. *Energy & Fuels* 27: 5440-5448.

Francis, A. and Vilminot, S. (2013). Crystallisation kinetics of mullite glass-ceramics obtained from alumina – silica wastes. *International Journal of Sustainable Engineering* 6: 74-81.

Fu, M., Jing Liu, J., Dong, X., Zhu, Li., Dong, Y., Hampshire, S. (2019). Waste recycling of coal fly ash for design of highly porous whisker-structured mullite ceramic membranes, *Journal of the European Ceramic Society* 39: 5320-5331

Garcia, C.D., Shahapurkar, K., Doddamani, M., Mohan Kumar, G.C. and Prabhakar, P. (2018). Effect of arctic environment on flexural behavior of fly ash cenosphere reinforced epoxy syntactic foams. *Composites Part B: Engineering* 151: 265-273.

Gerardin, C. (1994). Structural Investigation and Energetics of Mullite Formation from Sol-Gel Precursors. *Chemistry of Materials* 6: 160-170.

Gu, G., Ong, P.P. and Chu, C. (1999). Thermal stability of mesoporous silica molecular sieve. *Journal of Physics and Chemistry of Solids* 60: 943-947.

Guo, A., Liu, J., Xu, R., Xu, H. and Wang, C. (2010). Preparation of mullite from desilication-flyash. *Fuel* 89: 3630–3636.

Gupta, R.C. (2016). *Fuels, furnaces and refractories*. Delhi, India: PHI Learning Pvt Ltd.

Han, L., Deng, X., Li, F., Huang, L., Pei, Y., Dong, L., Li, S., Jia, Q., Zhang, H. and Zhang, S. (2018). Preparation of high strength porous mullite ceramics via combined foam-gelcasting and microwave heating. *Ceramics International* 44: 14728-14733.

Han, Y., Zhou, L., Liang, Y., Li, Z., Zhu, Y. (2020). Fabrication and properties of silica/mullite porous ceramic by foam-gelcasting process using silicon kerf waste as raw material, *Materials Chemistry and Physics* 240: 122248

Harbison, W. (2005). *Handbook of Refractory Practice*. Mount Union, PA, USA: Harbison-walker refractories Co.

Hossain, S.K.S., Pyare, R., Roy, P.K. (2020). Synthesis of in-situ mullite foam using waste rice husk ash derived sol by slip-casting route, *Ceramics International* 46: 10871-10878

Huirache-Acuna, R., Nava, R., Peza-Ledesma, C.L., Lara-Romero, J., Alonso-Nunez, G., Pawelec, B. and Rivera-Munoz, E.M. (2013). SBA-15 mesoporous silica as catalytic support for hydrodesulfurization catalysts - Review. *Materials* 6: 4139-4167.

Huo, P., Yan, Y., Li, S., Li, H. and Huang, W. (2010). Floating photocatalysts of fly-ash cenospheres supported AgCl/TiO_2 films with enhanced Rhodamine B photodecomposition activity. *Desalination* 256: 196-200.

Huo, W., Zhang, X., Chen, Y., Lu, Y., Liu, J., Yan, S., Wu, J. and Yang, J. (2018). Novel mullite ceramic foams with high porosity and strength using only fly ash hollow spheres as raw material. *Journal of the European Ceramic Society* 38: 2035-2042.

Inoue, H., Sekizawa, K., Eguchi, K. and Arai, H. (1997). Thermal stability of hexaaluminate film coated on SiC substrate for high-temperature catalytic application. *Journal of the American Ceramic Society* 80: 584–88.

International Energy Agency (IEA) Statistics.(2017). *Key world energy statistics: 2017 edition*. France: International Energy Agency.

Johansson, E.M., Danielsson, K.M.J., Ersson, A.G. and Järäs, S.G. (2002). Development of hexaaluminate catalysts for combustion of gasified biomass in gas turbines. *J. Eng. Gas Turbines Power* 124: 235-238.

Johansson, E.M., Papadias, D., Thevenin, P.O., Ersson, A.G., Gabrielsson, R., Menon, P.G., Björnbom, P.H. and Järäs, S.G. (1999). Combustion for gas turbine applications. In J.J. Spivey (Ed.) *Catalysis Specialists Periodical Reports* (pp. 183-235). Cambridge, UK: Royal Society of Chemistry.

Jung, J.S. and Park, H.C. (2001). Mullite ceramics derived from coal fly ash. *Journal* of Materials *Science Letters 20*: 1089–1091.

Khattab, R.M., EL-Rafei, A.M. and Zawrah, M.F. (2012). In situ formation of sintered cordierite–mullite nano–micro composites by utilizing of waste silica fume. *Materials Research Bulletin* 47: 2662–2667.

Khattab, R.M., EL-Rafei, A.M. and Zawrah, M.F. (2018). Fabrication of Porous TiO_2 Ceramics Using Corn Starch and Graphite as Pore Forming Agents. *InterCeram*: *International Ceramic Review* 67: 30-35.

klug, F.J., Prochazka, S. and Doremus, R.H. (1987). Alumina-silica phase diagram in the mullite region. *Journal of the American Ceramic Society,* 70: 750-759.

Kolay, P.K. and Singh, D.N. (2001). Physical, chemical, mineralogical, and thermal properties of cenospheres from an ash lagoon. *Cement and Concrete Research* 31: 539- 542.

Kühn, B. and Schadrack, R. (2009). Thermal expansion of synthetic fused silica as a function of OH content and fictive temperature. *Journal of Non-Crystalline Solids* 355: 323–326.

Kušar, H.M.J., Ersson, A.G. and Järäs, S.G. (2003). Catalytic combustion of gasified refuse-derived fuel. *Applied Catalysis B: Environmental* 45: 1-11.

Kušar, H.M.J., Ersson, A.G., Thevenin, P.O. and Järäs, S.G. (2001). Sulfur poisoning in catalytic combustion of industrial waste. *Studies in Surface Science and Catalysis* 139: 463-470.

Kusnierova, M., Prascakova, M., Matysek, D. and Cablík, V. (2011). Mullitization of black coal fly ashes. *Acta Montanistica Slovaca* 16: 192–196.

Lee, S., Tanaka, H. and Aoyagi, T. (2009). Densification of AlN using boron and carbon additives. *Journal of the European Ceramic Society* 29: 2021–2027.

Li, J., Ma, H. and Huang, W. (2009). Effect of V_2O_5 on the properties of mullite ceramics synthesized from high aluminum fly ash and bauxite. *Journal of Hazardous Materials* 166: 1535–1539.

Li, L., Cao, G., Zhao, R., Wang, L., Wu, S. (2020). High-porosity whisker-mullite/corundum membrane support prepared from recycled industrial waste coal cinder, *Ceramics International* 46: 4086-4094

Li, S., Du, H., Guo, A., Xu, H. and Yang, D. (2012). Preparation of self-reinforcement of porous mullite ceramics through in situ synthesis of mullite whisker in flyash body. *Ceramics International* 38: 1027–1032.

Lin, B., Li, S., Hou, X. and Li, H. (2015). Preparation of high performance mullite ceramics from high aluminum fly ash by an effective method. *Journal of Alloys and Compounds* 623: 359–361.

Liu, F., Wang, J., Qian, X. and Hollingsworth, J. (2017). Internal curing of high performance concrete using cenospheres. *Cement and Concrete Research* 95: 39-46.

Liu, R. and Xiang, D. (2021). Recycling photovoltaic silicon waste for fabricating porous mullite ceramics by low-temperature reaction sintering, *Journal of the European Ceramic Society* 41: 5957-5966

Liu, S., Ma, W., Zhang, Y., Zhang, Y. and Qi, K. (2018). Sequential Transformation Behavior of Iron-Bearing Minerals during Underground Coal Gasification. *Minerals* 8: 90.

MacKenzie, K.J.D., Brown, I.W.M. (1975). Devitrification of aluminosilicate glasses under applied electric fields. *Journal of Thermal Analysis* 7: 619–633.

Mahlambi, M.M., Mishra, A.K., Mishra, S.B., Krause, R.W., Mamba, B.B. and Raichur, A.M. (2012). Comparison of rhodamine B degradation under UV irradiation by two phases of titania nano-photocatalyst. *Journal of Thermal Analysis and Calorimetry* 110: 847-855.

Mahnicka-Goremikina, L., Svinka, R. and Svinka, V. (2018). Influence of ZrO_2 and WO_3 doping additives on the thermal properties of porous mullite ceramics. *Ceramics International* 44: 16873-16879.

Martins, I.M., Sousa, J.B., Catarino, L., Vieira, M.T. and Oliveira, M. (2002). The Formation of Mullite from Rock Wastes Containing Alumina and Silica. *Key Engineering Materials* 230: 380–383.

Martins, I.M., Vieira, S., Livramento, V., Sousa, J., Delmas, F., Oliveira, M.M. and Viera, M.T. (2004). Manufacture of Ceramic Products Using Inertized Aluminum Sludges. *Materials Science Forum* 456: 822–826.

Mondal, A., Maitra, S., Chandra, S. and Mitra, N.K. (2008). Alumina-Mullite Composites through Interaction of Bauxite and Fly Ash. *Transactions of the Indian Ceramic Society* 67: 81-85.

Mizuno, M. (1991). Microstructure, Microchemistry, and Flexural Strength of Mullite Ceramics. *Journal of the American Ceramic Society* 74: 3017–3022.

Nakata, M. and Suganuma, K. (2005). Effect of Internal Structure on Thermal Properties of Alumina/Aluminum Composites Fabricated by Gelate-Freezing and Partial-Sintering Process, respectively. *Materials Transactions* 46: 130-135.

Ngu, L., Wu, H. and Zhang, D. (2007). Characterization of Ash Cenospheres in Fly Ash from Australian Power Stations. *Energy and Fuels* 21: 3437-3445.

Ohji, T. and Fukushima, M. (2012). Macro-porous ceramics: Processing and properties. *International Materials Reviews* 57: 115–131.

Oliveira, F.A.C., Livramento, V. and Delmas, F. (2007). Novel mullite-based ceramics manufactured from inorganic wastes I. Densification behaviour. *The Journal of Materials Processing Technology* 6: 101–108.

Padhi, L.N., Sahu, P., Sahoo, N., Singh, S.K. and Tripathy, J.K. (2017). A Novel Process for Synthesis of Iron-Alumina Spinel and Its Application in Refractory for Cement Rotary Kiln. *Transactions of the Indian Ceramic Society* 76: 196-201.

Park, Y.M., Yang, T.Y., Yoon, S.Y., Stevens, R. and Park, H.C. (2007). Mullite whiskers derived from coal fly ash. *Materials Science and Engineering A 455*: 518–522.

Pask, J.A. (1996). Importance of starting materials on reaction and phase equilibria in the Al_2O_3–SiO_2 system, *Journal of the European Ceramic Society* 16: 101–108.

Peretz, I. and Bradt, R.C. (1983). Linear thermal expansion coefficients of mullite-matrix aluminosilicate refractory bodies, *Journal of the American Ceramic Society* 66: 823–829.

Pivinskii, Y.E., Dyakin, P.V., Kolobov, A.Y. (2016). Research in the Area of Preparing Materials Based on Fuzed Quartz HCBS. Part 9. Effect of Alkali Additions on Material Cristobalitization and Thermal Expansion After Nonisothermal Heating. *Refractories and Industrial Ceramics* 57**:** 135–140.

Pyzik, A., Ziebarth, R., Han, C., and Yang, K. (2011). High-porosity acicular mullite ceramics for multifunctional diesel particulate filters. *The International Journal of Applied Ceramic Technology* 8: 1059-1066.

Qian, H., Cheng, X., Zhang, H. and Zhang, R. (2014). Preparation of Porous Mullite Ceramics Using Fly Ash Cenosphere as a Pore-Forming Agent by Gelcasting Process. *The International Journal of Applied Ceramic Technology* 11: 858–863.

Raask, E. (1968). Cenosphere in Pulverized-Fuel Ash. *Journal of the Institute of Fuel* 41: 339- 344.

Rani, D.A., Jayaseelan, D.D., Gnanam, F.D. (2001). Densification behavior and microstructure of gel-derived phase-pure mullite in presence of sinter additives, *Journal of the European Ceramic Society* 21: 2253–2257.

Ranjbar, N. and Kuenzel, C. (2017). Cenospheres: A review. *Fuel* 207: 1-12.

Rashad, M., Sabu, U., Logesh, G. and Balasubramanian, M. (2019). Development of porous mullite and mullite-Al_2O_3 composite for microfiltration membrane applications. *Separation and Purification Technology* 219: 74–81.

Ravi Kumar, D.V., Seenappa, Asha, P.B. and Prakash Rao, C.R. (2018). Influence of percent filler on tensile strength, impact strength and wear properties of the Al7075 cenosphere composite. *Materials Today: Proceedings* 5: 11697-11708.

Ribeiro, M.J. and Labrincha, J.A. (2008). Properties of sintered mullite and cordierite pressed bodies manufactured using Al-rich anodising sludge. *Ceramics International 34*: 593–597.

Ribeiro, M.J., Tulyagavov, D.U., Ferreira, J.M. and Labrincha, J.A. (2005). High temperature mullite dissolution in ceramic bodies derived from Al-rich sludge. *Journal of the European Ceramic Society* 25: 703-710.

Rijswijk, W.V. and Shanefield, D.J. (1990). Effects of Carbon as a Sintering Aid in Silicon Carbide. *Journal of the American Ceramic Society* 73: 148-149

Sadik, C., Al Albizane, A., and El Amrani, I. (2013). Characterization of elaborated Moroccan mullite to improving porous refractories quality. *Cerâmica* 59: 609-613.

Sadik, C., Amrani, I.E., and Albizane, A. (2014). Recent advances in silica-alumina refractory: A review. *Journal of Asian Ceramic Societies* 2: 83–96.

Saruhan, B., Albers, W., Schneider, H., Kaysser, W.A. (1996). Reaction and sintering mechanisms of mullite in the systems cristobalite/α-Al_2O_3 and amorphous SiO_2/α-Al_2O_3, *Journal of the European Ceramic Society* 16: 1075–1081.

Schneider, H., Komarneni, S. (2005). *Mullite*. Weinheim, Germany: Wiley VCH.

Schneider, H., Seifert-Kraus, U., Majdic, A. (1982). Microchemistry of refractory-grade bauxites, *American Ceramic Society Bulletin* 61:741–745.

Schneider, H., Schreuer, J. and Hildmann, B. (2008). Structure and properties of mullite - A review. *Journal of the European Ceramic Society* 28: 329-344.

Sembiring, S., Simanjuntak, W., Manurung, P., Asmi, D. and Low, I.M. (2014). Synthesis and characterisation of gel derived mullite precursors from rice husk silica. *Ceramics International* 40: 7067–7072.

Serra, M.F., Conconi, M.S., Gauna, M.R., Suárez, G., Aglietti, E.F. and Rendtorff, N.M. (2016). Mullite ($3Al_2O_3·2SiO_2$) ceramics obtained by reaction sintering of rice husk ash and alumina, phase evolution, sintering and microstructure. *Journal of Asian Ceramic Societies* 4: 61–67.

Sing, K.S.W., Everett, D.H., Haul, R.A.W., Moscou, L., Pieroti, R.A., Rouquerol, J. and Siemieniewska, T. (1985). Reporting Physisorption Data for Gas/Solid Systems with Special Reference to the Determination of Surface Area and Porosity. *Pure and Applied Chemistry* 57: 603-619.

Sousa, L.L., Souza, A.D.V., Fernandes, L., Arantes, V.L., Salomão, R. (2015). Development of densification-resistant castable porous structures from in situ mullite. *Ceramics International* 41: 9443–9454.

Souto, A. and Guitian, F. (2002). Novel method for obtaining corundum layers of high surface area on ceramic supports for high-temperature catalysis. *Journal of the American Ceramic Society 85*: 1823-1826.

Souza, A.D.V., Arruda, C.C., Fernandez, L., Antunes, M.L.P., Kiyohara, P.K., Salomão, R. (2015). Characterization of aluminum hydroxide (Al(OH)3) for its use as a porogenic agent in castable ceramics, *Journal of the European Ceramic Society* 35: 803–812.

Souza, L.P.D.F. and Mansur, H.S. (2004). Production and characterization of ceramic pieces obtained by slip casting using powder wastes. *The Journal of Materials Processing Technology* 145: 14–20.

Suriyanarayanan, N., Kannannithin, K. V. and Bernardo, E. (2009). Mullite glass ceramic production from coal ash and alumina by high temperature plasma. *Journal of Non-Oxide Glasses* 1: 247-260.

Talou, M.H., Moreno, R., and Camerucci, M.A. (2014). Porous Mullite Ceramics Formed by Direct Consolidation Using Native and Granular Cold-Water-Soluble Starches. *Journal of the American Ceramic Society* 97: 1074–1082.

Tamm, K., Kivi, I., Anderson, E., Trikkel, A., Möller, P., Nurk, G. and Lust, E. (2012). Influence of Graphite Pore Forming Agents on the Structural and Electrochemical Properties of Porous Ni-CGO Anode. *Journal of the Electrochemical Society* 159: F849−F857.

Tan, H. (2011). Preparation of mullite whiskers from coal fly ash using sodium sulfate flux. *International Journal of Mineral Processing* 100: 188–189.

Trueba, M. and Trasatti, S.P. (2005). γ-Alumina as a support for catalysts: A review of fundamental aspects. *European Journal of Inorganic Chemistry* 17: 3393-3403.

Vieira, M.T., Catarino, L., Oliveira, M., Sousa, J., Torralba, J.M., Cambronero, L.E.G., Gonzalez-Mesones, F.L. and Victoria, A. (1999). Optimization of the sintering process of raw material wastes. *The Journal of Materials Processing Technology* 93: 97–101.

Waddar, S., Pitchaimani, J. and Doddamani, M. (2018). Snap-through buckling of fly ash cenosphere/epoxy syntactic foams under thermal environment. *Thin-Walled Structures* 131: 417-427.

Wahl, F. M., Grim, R. E. and Graf, R. B. (1961). Phase transformations in silica as examined by continuous X-ray diffraction. *The American Mineralogist* 46: 196-208.

Wang, J., Zhang, M., Li, W., Chia, K. and Liew, R.J.Y. (2012). Stability of cenospheres in lightweight cement composites in terms of alkali–silica reaction. *Cement and Concrete Research* 42: 721-727.

Wang, M., Jia, D., He, P. and Zhou, Y. (2011). Microstructural and mechanical characterization of fly ash cenosphere/metakaolin-based geopolymeric composites. *Ceramics International* 37: 1661–1666.

Wang, W., Shi, Z., Wang, Z. and Wang, S. (2018). Phase transformation and properties of high-quality mullite ceramics synthesized using desert drift sands as raw materials. *Materials Letters* 221: 271–274.

Wang, X., Guo, W., Kan, Y., Zhang, G. and Wang, P. (2011). Densification behavior and properties of hot-pressed ZrC ceramics with Zr and graphite additives. *Journal of the European Ceramic Society* 31: 1103-1111.

Xin, Q. (2011). *Diesel Engine System Design*. Cambridge, UK: Woodhead Publishing.

Xu, G., Ma, Y., Cui, H., Ruan, G., Zhang, Z. and Zhao, H. (2014). Preparation of porous mullite–corundum ceramics with controlled pore size using bioactive yeast as pore-forming agent. *Materials Letters* 116: 349-352.

Yang, F., Li, C., Lin, Y. and Wang, C.A. (2012). Effects of sintering temperature on properties of porous mullite/corundum ceramics. *Materials Letters* 73: 36-39.

Yang, M., Li, J., Man, Y., Peng, Z., Zhang, X. and Luo, X. (2020). A novel hollow alumina sphere-based ceramic bonded by in situ mullite whisker framework. *Materials & Design*. 186: 108334.

Yang, T.Y., Ji, H.B., Yoon, S.Y., Kim, B.K. and Park, H.C. (2010). Porous mullite composite with controlled pore structure processed using a freeze casting of TBA-based coal fly ash slurries. *Resources, Conservation and Recycling* 54: 816–820.

Yang, Y., Hu, Z., Chang, Q., Liu, H., Yang, K. and Wang, Y. (2018). Effect of Type and Content of Pore-forming Agents on Properties of Porous Alumina Membrane Support. *IOP Conference Series: Materials Science and Engineering* 452: 022047.

Yi, F., DeLisio, J.B., Nguyen, N., Zachariah, M.R., LaVan, D.A. (2017). High heating rate decomposition dynamics of copper oxide by nanocalorimetry-coupled time-of-flight mass spectrometry, *Chemical Physics Letters*, 689: 26-29

Yugeswaran, S., Ananthapadmanabhan, P.V., Kobayashi, A. and Lusvarghi, L. (2011). Transferred arc plasma processed mullite from coal ash and bauxite. *Ceramics International* 37: 3437–3444.

Zhang, X., Wu, G., Yao, T. et al. (2011). Characterization of individual fly ash particles in surface snow at Urumqi Glacier No. 1, Eastern Tianshan. *Chinese Science Bulletin* 56: 3464–3473

Zhu, L., Dong, Y., Hampshire, S., Cerneaux, S. and Winnubst, L. (2015). Waste-to-resource preparation of a porous ceramic membrane support featuring elongated mullite whiskers with enhanced porosity and permeance. *Journal of the European Ceramic Society 35*: 711–721.

Zhu, L., Dong, Y., Li, L., Liu, J. and You, S. (2015). Fabrication of mullite-whisker-structured porous. *RSC Advances* 5: 11163–11174.

Zyrkowski, M., Neto, R.C., Santos, L.F. and Witkowski, K. (2016). Characterization of fly-ash cenospheres from coal-fired power plant unit. *Fuel* 174: 49–53.