DEVELOPMENT OF THE PORCELAIN TILES BY THE PARTIAL SUBSTITUTION OF FELDSPAR WITH FLY ASH

NUR AZUREEN BINTI ALWI KUTTY

A thesis submitted in
fulfilment of the requirement for the award of the
Degree of Master of Science

Faculty of Applied Sciences and Technology
Universiti Tun Hussein Onn Malaysia

NOVEMBER 2020

Special dedicated to my beloved family

ACKNOWLEDGEMENT

First and foremost, I would like to express my gratitude to my supervisor, Assoc. Prof. Dr. Mohamad Zaky Noh for his guidance, helpful advice, endless encouragement and enormous patience throughout the development of this research. Special thanks to my co-supervisor, Dr. Mohd Zul Hilmi Mayzan for his guidance, helpful discussion, invaluable suggestions and opinions during the period of the sample preparation. I am so grateful to the Universiti Tun Hussein Onn Malaysia for the generous financial support, which giving me an opportunity to further my study.

Many thanks to Mr. Kamarul Affendi Hamdan, Mr. Shahrul Mahadi Samsudin, Mr. Fazlanuddin Hanur Harith, Mr. Mohd Yusof Mohd Sahil, Mr. Hasrul Ismail, Mr. Tarmizi Nasir, Mr. Anuar Ismail and Mr. Bahtiar Mohd Basri that had spent plenty of time in providing excellent technical assistance for all the characterization involve in this study.

Most of all I would like to express my deepest appreciation and thanks to my family and all my friends for their unconditional love, constant encouragement and endless support throughout the journey in completing my research.

ABSTRACT

Fly ash properties are unusual among engineering materials. Typically used for embankment construction, fly ash is well known in the production of cement, concrete and brick. Fly ash is one of the palm oil waste products from the combustion of palm fiber and shells in the boiler which are collected at the multi-cyclone collectors. In this research, feldspar is gradually replaced by fly ash compositions of 0 – 25 wt. %. The samples were mixed for 12 hours, pressed with a load of 3 tonnes and isostatically pressed by using CIP with a pressure of 100 MPa. The samples were sintered at the temperature range of 1100 – 1300 °C. An investigation on the physical and mechanical properties as well as the crystalline phase and microstructure of porcelain were evaluated in this study. Through XRF analysis, the presence of fluxing component in fly ash significantly proved its potential as fluxing agent in porcelain. The highest strength of the porcelain obtained at the replacement of 5 wt. % of fly ash sintered at 1250 °C concurrently shows it as the best composition of fly ash and the best sintering temperature. Maximum compressive strength of 105.40 MPa and higher Vickers microhardness value obtained through this composition. In fact, the percentage of the total mass loss was increased up to 9.30 %. The bulk density value of the porcelain is reduced to 2.34 g/cm^3, which almost 2.5 % loss of density. Lower apparent porosity achieved at this compositions with 0.22 %, indicating almost complete densifications takes place. The percentage of mullite content was found to be increased with existence of fly ash in porcelain compositions. SEM studied revealed that intense interlocking and uniform distribution between the primary and secondary mullite in glassy matrix are contributed in achieving higher densification of porcelain. It is concluded that the utilization of fly ash as fluxing component is highly suitable in porcelain and the replacement of 5 wt. % of fly ash successfully improvised the properties and the microstructure of the porcelain with attaining higher mechanical strength.

ABSTRAK

Ciri-ciri abu terbang adalah luar biasa di kalangan bahan-bahan kejuruteraan. Biasanya digunakan untuk pembinaan tambak, abu terbang terkenal dalam pengeluaran simen, konkrit dan batu bata. Abu terbang merupakan salah satu daripada sisa kelapa sawit yang terhasil dari pembakaran serat dan kulit biji sawit di dalam dandang yang dikumpulkan di pengumpul pelbagai siklon. Dalam kajian ini, feldspar digantikan secara berkala pada komposisi 0 – 25 %. Sampel dicampur selama 12 jam, ditekan dengan bebanan sebanyak 3 tan dan ditekan secara isostatik menggunkan CIP di bawah tekanan 100 MPa. Sampel disinter pada jarak suhu 1100 – 1300 °C. Penyiasatan terhadap sifat fizikal dan mekanikal, serta fasa-fasa hablur dan struktur mikro porselin dinilai dalam kajian ini. Melalui analisis XRF, kehadiran komponen fluk dalam abu terbang dengan ketara membuktikan potensinya sebagai agen fluk dalam porselin. Kekuatan maksimum porselin diperoleh pada penggantian 5 % berat abu terbang disinter pada 1250 °C sekaligus menunjukkan ia sebagai komposisi abu terbang dan suhu persinteran yang terbaik. Kekuatan mampatan maksimum iaitu 105.40 MPa dan nilai kekerasan mikro Vickers yang tinggi diperoleh melalui komposisi ini. Malah, peratusan jumlah kehilangan jisim meningkat sehingga 9.30 %. Ketumpatan pukal porselin berkurang sehingga 2.34 g/cm^3, dimana hampir 2.5% kehilangan ketumpatan pukal berlaku pada komposisi ini. Keliangan ketara yang lebih rendah diperoleh sebanyak 0.22 %, menunjukkan berlakunya kepadatan yang hampir lengkap. Peratusan kandungan mullite didapati meningkat dengan kehadiran abu terbang dalam komposisi porselin. Kajian SEM membuktikan bahawa pengedaran sengit dan taburan seragam di antara mullit primer dan sekunder dalam matrik berkaca menyumbang dalam mencapai kepadatan porselin yang lebih tinggi. Kesimpulannya, penggunaan abu terbang sebagai komponen fluk sangat sesuai di dalam penghasilan porselin dan penggantian sebanyak 5 % berat abu terbang berjaya menambah baik sifat-sifat dan mikrostruktur porselin dengan pencapaian kekuatan mekanikal yang lebih tinggi.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

A - Area

d - Distance

F - Force

n - Integer

α - Alpha

β - Beta

θ - Angle

λ - Wavelength

π - Pi

$<$ - Less than

d^2 - Area of the Indentation (mm^2)

d_i - Initial Diameter

d_f - Final Diameter

h_i - Initial Height

h_f - Final Height

m_i - Initial Mass

m_f - Final Mass

W_1 - Dry Weight

W_2 - Suspended Weight

W_3 - Soaked Weight

ρ_w - Density of Water (0.99777 g/cm^3)

ASTM - American Society for Testing and Materials

AE - Auger Electrons

BSE - Backscattered Electrons

BPR - Ball to Powder Ratio

BS - British Standard

CCD - Charge-coupled Device
CL - Cathodoluminescence
CIP - Cold Isostatic Pressing
EDS - Energy Dispersive Spectroscopy
FA - Fly Ash
FAHM - Fly-Ash Hollow Microsphere
FP - Fly ash Porcelain
HF - Hydrofluoric acid
IHM - Inorganic Hollow Microsphere
ISO - International Standards Organization
ICDD - International Centre for Diffraction Data
LFC - Lightweight Fly ash Ceramics
LSC - Lightweight Sludge Ceramics
NP - Normal Porcelain
OHM - Organic Hollow Microsphere
OPR - Ordinary Portland Cement
POFA - Palm Oil Fuel Ash
PVA - Polyvinyl Alcohol
PSC - Pressure Slip Casting
RHA - Rice Husk Ash
SE - Secondary Electrons
SEM - Scanning Electron Microscopy
XRF - X-ray Fluorescence
XRD - X-ray Diffraction

LIST OF PUBLICATIONS

Paper

Kutty, N. A. A., & Noh, M. Z (2016). Influence of Phlogopite on the Physico-Mechanical Properties of Porcelain. *Journal of Science and Technology, 8*(1), 9–12.

Kutty, N. A. A., Noh, M. Z., Mayzan, M. Z. H., & Iya, S. G. D. (2018). Influence on the Phase Formation and Strength of Porcelain by Partial Substitution of Fly Ash Compositions. *International Journal of Engineering & Technology, 7*(4.30), 271–275.

Iya, S. G. D, Noh, M. Z., Ab Razak, S. N., Sharip, N., Jasim, M. J., & Kutty, N. A. A. (2020). Developed Formulation Model by the Addition of SiO_2 for Optimum Physicomechanical Properties of Porcelain using Modified Palm Oil Fuel Ash (POFA). *International Journal of Nanoelectronics and Materials,* 13(2), 401 – 410.

Conference

Kutty, N. A. A., Noh, M. Z., Mayzan, M. Z. H., & Iya, S. G. D. (2018). Influence of Different Compositions of Fly Ash as Fluxing Agent in Porcelain. *Advanced Materials Characterization Technique, 16th – 17th August 2017, Genting Highlands, Malaysia* (Poster presentation)

CHAPTER 1

INTRODUCTION

1.1 Background of the study

Ceramic is an inorganic and non-metallic material, and its processing generally involves high temperature. Ceramics materials are grouped according to its mineralogical such as silicate, oxide, non-oxide, nitride and carbide. Besides, ceramic can also be categorized into traditional and advanced ceramics. Traditional ceramics are based on clay and silica, and examples of traditional ceramics are pottery, whiteware, earthenware, stoneware, chinaware and porcelain. In fact, traditional ceramic has been used over 25,000 years, while advanced ceramics were developed within last 100 years (Carter & Norton, 2007). One example of traditional ceramic was invented by the Chinese during T'ang dynasty which namely as white ceramic (Snehesh, 2014).

Porcelain or tri-axial porcelain consists of three different raw materials which are clay or kaolin, feldspar and quartz. Standard compositions of porcelain are approximately 50 % of kaolin, 25 % of quartz and 25 % of feldspar (Koca et al., 2012). Kaolin is the main based raw materials of porcelain where it provides plasticity for forming process. Meanwhile, feldspar helps in enhancing vitrification, and quartz functions as a filler which is able to reduce the shrinkage during firing (Kitouni & Harabi, 2011). Reactivity among these three raw materials provide porcelain with extremely good properties such as less porous, low permeability and elasticity, high resistance to chemical attack and thermal shock, translucence and high hardness rating (Snehesh, 2014).

Regarding its application, porcelain tiles is one of the new products compared to other ceramic tiles, and it shows an increasing rate in its market trends recently. Porcelain tile is a high quality product, and it stands out from other products due to its excellent technical properties. It is a vitrified ceramic product with extremely low porosity (< 0.5 %), and a very low percentage of closed porosity which is < 10 % (De Noni et al., 2011; Sánchez et al., 2010). It also has low water absorption, highly creative design, and high abrasion resistance which results in higher mechanical strength (García-Ten et al., 2012). Although porcelain composition can influence the characteristic of the end-product, the sintering temperature is also one of the most important factors in the fabrication of porcelain tiles. The changes in microstructure and vitrification behaviour are dependent on the sintering temperature because it brings out the significant changes in the densification, and it improves the strength of the porcelain tiles (Acchar & Eduardo, 2015).

Over the last few years, modification on the raw materials of porcelain has been executed by utilization of waste materials where it improves the physical and mechanical properties of porcelain. Most of the modifications are focused on the replacement of quartz with waste materials such as fly ash, rice husk ash (RHA), glass waste and slag. Among all waste materials, fly ash had been widely reported on its replacement with quartz in improving the mechanical properties of porcelain (Acchar & Dultra, 2015; Das et al., 2013. However, there are limited studies on the production of lightweight porcelain by the substitution of fly ash. Fly ash is a residue generated from the process of combustion where it is in form of very fine powder and highly content of silica (SiO_2) and alumina (Al_2O_3). In recent years, fly ash is widely used in ceramics due to its potential as a filler and fluxing agent; hence, simultaneously improves its physical and mechanical properties.

1.2 Problem statement

Porcelain tile is a high quality product with excellent technical properties, and it is being commercialized worldwide. Research on the improvise the physical and mechanical properties of porcelain tiles is highly significant, and extremely could expand the uses of this tile for the next few years, since porcelain tiles are being commercialized worldwide which in turn will increase its demand in construction industry.

Over the past 7 years, investigation on the replacement of the raw materials of porcelain with waste materials are mostly including rice husk ash, glass waste, soda lime scrap and palm oil fuel ash. However, the utilization of fly ash in the fabrication of porcelain tiles still remains unclear. The replacement of fly ash on feldspar has not been widely reported compared to quartz. Fly ash is known for its high alumina (Al_2O_3) and silica (SiO_2) content, both of which have potential as a fluxing agent and it is believed could improve the mechanical strength of the porcelain (Das et al., 2013). Fly ash properties are unusual among engineering materials. It has a large uniformity coefficient, and it consists of clay-sized particles (Kim et al., 2014).

Production of porcelain consumes of large amount of kaolin, feldspar and quartz. In the present study, feldspar will be replaced with fly ash in the tri-axial porcelain according to a few compositions that have been highlighted. Utilization of fly ash is expected could improve the properties of the porcelain tiles depending to the compositions of fly ash and other parameters that has been considered in this work. Feldspar is the second most important raw material which acts as a fluxing agent that provides high vitrification of clay bodies by reducing the melting point (Acchar & Eduardo, 2015). The most common fluxes used in clay bodies are potassium oxide and sodium oxide. Basically, two properties which make feldspars useful for industries are their alkali and alumina content (Ogundare et al., 2016).

Therefore, the substitution of fly ash will minimize the cost of the raw materials. Malaysia produces almost 3 million tonnes of fly ash per annum, making fly ash as one of the highest generated waste materials and the disposal of these waste materials contribute to global warming and emission of greenhouses gases (Yap et al., 2013). In fact, the availability of substitution of feldspar with fly ash would encourage the competitiveness of using waste product in ceramic industries. In addition, the environmental pollution issues could also be mitigated through this work.

1.3 Objectives of the study

The study aims to develop the porcelain tiles with improve its properties by substituting feldspar with fly ash in the porcelain. In order to achieve the mentioned aim, a few objectives can be divided as follow:

1. To determine the best composition of fly ash in order to improve the physical and mechanical properties of the porcelain.
2. To determine the suitable sintering temperature of porcelain towards excellent physical and mechanical properties of porcelain.
3. To investigate the mineralogy and the microstructure of porcelain due to the substitution of fly ash.

1.4 Scope of the study

The scopes have been designed to make sure that the objectives of the study were implemented successfully. The scopes of the study are as follows:

1. Standard porcelain compositions (Koca et al., 2012): 50 wt. % of Kaolin, 25 wt. % of quartz and 25 wt. % of feldspar (feldspar are progressively replaced by fly ash from 0 wt. % up to 25 wt. %).
2. The sintering temperature of porcelain involved are 1100 °C, 1150 °C, 1200 °C, 1250 °C and 1300 °C.
3. Heating and cooling rate in the sintering process are 2 °C/min – 5 °C/min with 2 hours soaking time.
4. Pressure exerted in cold isostatic pressing (CIP) is 100 MPa.
5. Physical properties testing involved in this research are mass loss, volume shrinkage, apparent porosity and bulk density.
6. Mechanical properties testing involved in this research are Vickers microhardness and compressive strength.
7. Scanning Electron Microscope is used to evaluate the microstructure of the porcelain.
8. X-ray diffraction (XRD) analytical technique is used to investigate the mineralogical compositions of the porcelain.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Porcelain tiles is known as highly vitrified ceramic product which has lower water absorption rates (Acchar & Eduardo, 2015). There is two types of tiles commonly being used in tiles industry which are porcelain and ceramic tiles. Both of the tiles can look very similar but there is a distinct difference between them. The most significant identifying factor is the compositions of the raw materials, where porcelain tiles is made of 50 wt. % of kaolin, 25 wt. % of feldspar and 25 wt. % of quartz (Koca et al, 2012). Meanwhile, ceramic tiles is commonly made of by natural clay mixed with various formula with water and sometimes added with organic materials (Mishulovich & Evanko, 2003). However, porcelain tiles is costly due to its remarkable properties, including higher durability, higher thermal shock (Snehesh, 2014).

2.2 Ceramic

Ceramic is a non-metallic materials which is made up from metals or metalloid and non-metals. The word ceramic is originated from the Greek term *"Keramikos",* which means potteries or materials which have been burned out. There are various compositions of ceramics such as oxide, nitrides, carbides, sulphides, fluorides, graphite, etc. Ceramic can be classified into traditional and modern ceramic (Carter & Norton, 2007).

Traditional ceramic is clay-based ceramic such as pottery, whiteware, earthenware, stoneware, chinaware, porcelain, and technical ceramics. Pottery is made up of clay which has been sintered at the sintering temperature of less than 1200 °C. Stoneware and chinaware are typically produced by mixing of clay, feldspar and alumina which has been sintered around 1300 °C. Meanwhile, porcelain and technical ceramic are formed by mixture of clay, feldspar, and quartz which been sintered around 1300 °C and they can probably be sintered over 1300 °C. Traditional ceramics are commonly being applied in industry of tiles, sanitary ware, art ware and table ware (Chiang et al., 1997).

Meanwhile, modern ceramic or generally known as advanced ceramic includes alumina, zirconia, silicon carbide, silicon nitride and other types of nitride and carbide. Advanced ceramics are specifically invented by using ceramic materials that possess good thermal and electrical properties, corrosion or oxidation resistance and superior mechanical properties. The application of advanced ceramics are typically on laser host materials, piezoelectric ceramics, ceramics for dynamic random access memories (DRAMs) and nuclear fusion and fission application (Carter & Norton, 2007).

2.3 Porcelain

Porcelain is a type of ceramic that belongs to the group of silicate ceramics. It is defined as translucent vitreous ware, and it has very fine grained ceramic whiteware. Porcelain is originated from the France and Italy term *"porcella or porcellana"* in 16th century, which means translucent ceramic that uses clay as a major compound (Riley, 2009). Porcelain is being described as a tri-axial ceramic, which is comprised of three different main raw materials, namely clay, feldspar and quartz. Each raw material has its own respective roles. For instance, clay act as plastic materials, feldspar as a fluxing agent, whereas quartz act as a filler (Kitouni & Harabi, 2011).

The primary raw materials of porcelain are nepheline syenite and alumina. Both of the materials are commonly used as feldspar and quartz to improve the mechanical strength of the porcelain. Meanwhile, secondary raw materials include bentonite, bone ash, talc and zircon (Table 2.1), all of which are being commercialized in industry of whiteware ceramics (Carty & Senapati, 1998).

Table 2.1: Secondary raw materials of whiteware ceramics

Raw material	Nominal compositions	Common compositions	References
Bentonite	**Montmorillonite:** $(M^{2+})(M^{3+})_4(Si,Al)_8O_{20}(OH)_4\cdot nH_2O$	Not applicable	(Carty & Senapati, 1998)
	Montmorillonite: $(Al_2, Mg_3)\ (Si_4O_{10})\ (OH)_2\bullet nH_2O$	**Kaolinite:** $Al_2Si_2O_5(OH)_4$	(Widodo et al., 2019)
		Illite: $(K,H_3O)(Al,Mg,Fe)_2(Si,Al)_4O_{10}(OH)_2,(H_2O)$	
		Halloysite: $Al_2Si_2O_5(OH)_4$	
		Calcite: $CaCO_3$	
		Pyrite: FeS_2	
		Quartz: SiO_2	
Glass frits	No specific. Generally, frits depends on company specific due to the fusion of variety of minerals in furnace and quenching rapidly of molten materials.	**Anorthite–Diopside:** $CaO–MgO–Al_2O_3–SiO_2$	(Rasteiro et al., 2007)
		Cordierite–Indialite: $MgO–Al_2O_3–SiO_2$	
		Celsian: $BaO–Al_2O_3–SiO_2$	
		Anorthite: $CaO–Al_2O_3–SiO_2$	
		Nepheline: $Na_2O–Al_2O_3–SiO_2$	
Petalite (lithium feldspar)	$Li_2O\cdot Al_2O_3\cdot 6SiO_2$	**Sodium Oxide:** Na_2O	(Carty & Senapati, 1998)
		Potassium Oxide: K_2O	
Bone ash	$Ca_3(PO_4)_2$	**Silica:** SiO_2	(Zakaria & Haron, 2014)
		Alumina: Al_2O_3	
		Wollastonite: $CaSiO_3$	(Gouvêa et al., 2015)
		Anorthite: $CaAl_2Si_2O_8$	
Talc	$3MgO\cdot 2SiO_2\cdot 2H_2O$	**Chrysotile:** $Mg_3(Si_2O_5)(OH)_4$	(Carty & Senapati, 1998)
		Calcium Oxide: CaO	
Whiting	**Calcium Carbonate:** $CaCO_3$	**Magnesium Carbonate:** $MgCO_3$	(Carty & Senapati, 1998)
Zircon	**Zirconium Silicate:** $ZrO_2\cdot SiO_2$ / $ZrSiO_4$	Not applicable	(Carty & Senapati, 1998)
	Zirconium Silicate: $ZrSiO_4$	**Titanium Dioxide:** TiO_2	(Casasola et al., 2012)
		Tin(II) oxide: SnO_2	

Three constituents of the raw materials of porcelain are categorised in phase system [$K_2O \cdot Al_2O_3 \cdot SiO_2$]. Based on the phase diagram in Figure 2.1, the compositions of porcelain is high in silica (SiO_2), and the diagram clearly shows that the major constituents of its raw materials is clay which is comprised of 50 wt. % (Carty & Senapati, 1998). The compositions for tri-axial porcelain are 50 wt. % of clay, 25 wt. % of feldspar and 25 wt. % of quartz. The equilibrium relations between different phase changes due to the vitrification process which requires higher temperature. This leads to the phase formation which determines the microstructure of the porcelain (Iqbal & Lee, 2000). Due to the increased of feldspar, the vitrification can be achieved at lower temperature which leads to a reduction of high energy consumption and cost of sintering process (Kingery et al., 1976).

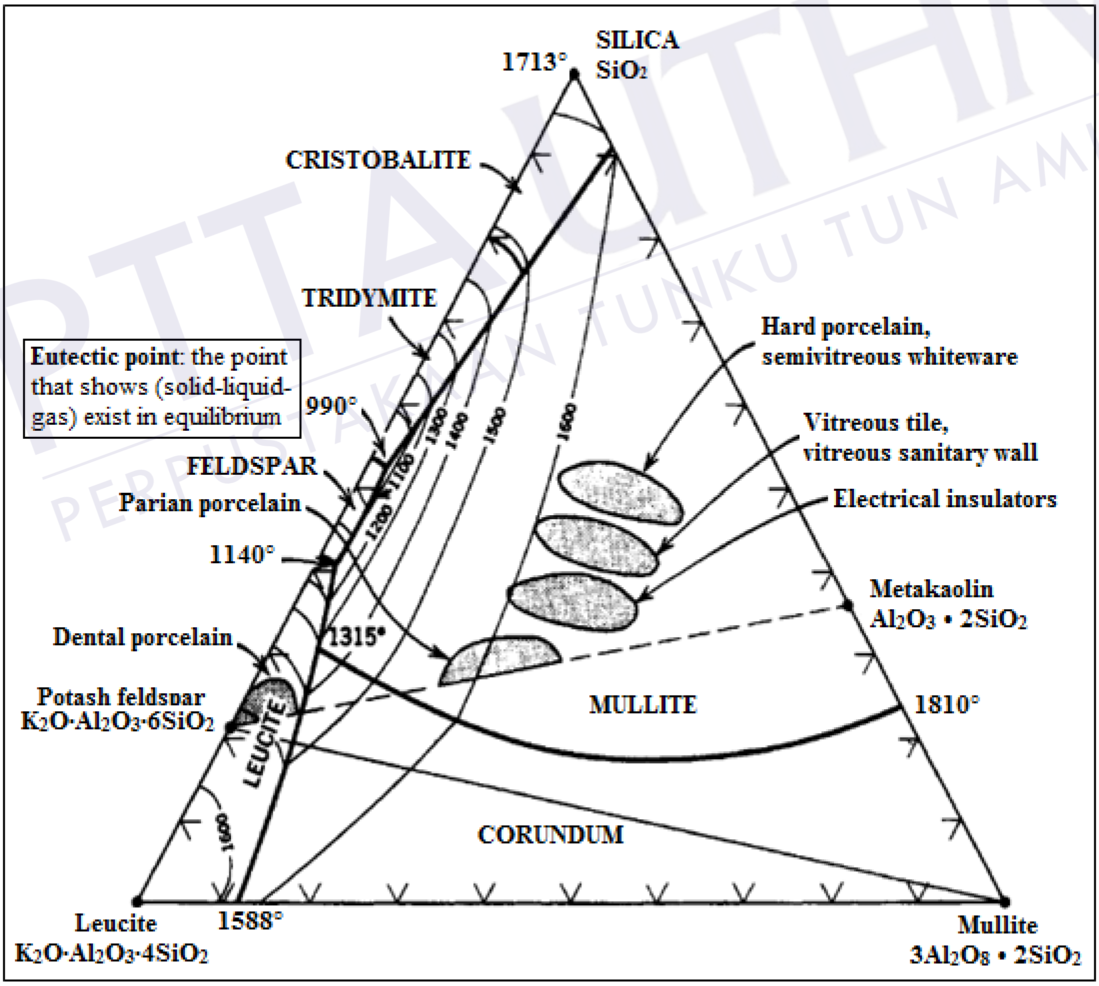

Figure 2.1: Compositions of various types of porcelain in [$K_2O \cdot Al_2O_3 \cdot SiO_2$] phase diagram (Carty & Senapati, 1998)

The ternary-phase of porcelain involves generating volumes of liquid, inducing vitrification and presents the translucency. Generally, the lowest liquid-forming temperature is 695 °C due to melting process of potash feldspar in contact with silicon dioxide. This process is also from the decomposition of the kaolinite. As the temperature increases, the liquid area progressively moves toward $Al_2O_3 – SiO_2$ axis. Kaolinite dehydroxylated to form metakaolin at the sintering temperature range of 450 – 550 °C, and the chemical equation is presented in Equation 2.1 (Shackelford & Doremus, 2008). Above the sintering temperature of 900 °C, metakaolin starts to form silicon-aluminium spinel phase and free silicon dioxide, resulting in the crystallizations of mullite above 1000 °C. This chemical reactions is presented in Equation 2.2 (Betala, 2014; Jamo, 2015).

However, the melting eutectic point was spotted at 990 °C. The eutectic temperature shows that all the three phases of solid-liquid-gas exists in equilibrium, where the feldspar particles in contact with decomposed kaolinite crystal with the presence of silicon dioxide. Generally, the eutectic temperature depends on the type of the feldspar (Carty & Senapati, 1998). Potash feldspar melts and forms a liquid phase containing silicon dioxide and leucite at 1140 °C, where it can help in the densifications of porcelain (Chiang et al., 1997). Based on Equation 2.3, the primary mullite forms by the decomposition of metakaolin at low temperature (~1000 °C), which at this state, the silicon dioxide is amorphous. Meanwhile, the silicon dioxide crystallizes at higher temperature and turns to cristobalite as presented in Equation 2.4.

$$\underset{\text{Kaolinite}}{Al_2SiO_2O_5(OH)_4} \xrightarrow{450\ \sim\ 550\,^{\circ}C} \underset{\text{Metakaolin}}{Al_2O_3 \bullet 2SiO_2 + 2H_2O} \tag{2.1}$$

$$\underset{\text{Metakaolin}}{Al2O_3 \bullet 2SiO_2} \xrightarrow{900\,^{\circ}C} \underset{\text{Al-Si Spinel}}{2Al_2O_3 \bullet 3SiO_2 + SiO_2} \tag{2.2}$$

$$\underset{\text{Al-Si Spinel}}{2Al_2O_3 \bullet 3SiO_2} \xrightarrow{1000\,^{\circ}C} \underset{\text{Pseudo-mullite}}{2(Al_2O_3 \bullet SiO_2) + SiO_2} \tag{2.3}$$

$$\underset{\text{Pseudo-mullite}}{3(Al_2O_3 \bullet SiO_2)} \xrightarrow{1250\ \sim\ 1440\,^{\circ}C} \underset{\text{Mullite + Cristobalite}}{3(Al_2O_3 \bullet 2SiO_2) + SiO_2} \tag{2.4}$$

REFERENCES

Abu-bakar, A. U., & Baharudin, K. S. (2012). Potential use of malaysian thermal power plants coal bottom ash in construction. *International Journal of Sustainable Construction Engineering & Technology*, *3*(2), 25–37.

Acchar, W., & Eduardo, J. V. D. (2015). *Ceramic materials from coffee bagasse ash waste* (2015th ed). Switzerland: Springer.

Aggarwal, P. S., Lele, R. V., & Mitra, B. L. (1977). Development of high strength whiteware bodies. *Transactions of the Indian Ceramic Society*, *36*(1), 12–16.

Ayala-Valderrama, D. M, & Gomez-Cuaspud, J. A. (2017). Characterization of fly ash, slag and glass hull for the obtaining of vitreous materials. *Journal of Physics: Conference Series*, *935*, 1–7.

Balfas, M., Wildan, M. W. J., & Kusnanto. (2008). The influence of sintering temperatures on the mechanical properties of glass ceramics made from coal fly ash and glass waste. *Materials Science Research India*, *5*(2), 227–234.

Balo, F., Ucar, A., & Lütfi Yücel, H. (2010). Development of the insulation materials from coal fly ash, perlite, clay and linseed oil. *Ceramics - Silikaty*, *54*(2), 182–191.

Betala, S. K. (2014). *Effect of replacement of quartz by fly ash in tri-axial porcelain bodies*. National Institute of Technology Rourkela. Bachelor Degree Thesis.

Bragança, S. R., Bergmann, C. P., & Hübner, H. (2006). Effect of quartz particle size on the strength of triaxial porcelain. *Journal of the European Ceramic Society, 26*, 3761–3768.

Carter, B., & Norton, G. (2007). *Ceramic materials science and engineering* (2nd ed). New York: Springer.

Carty, W. M., & Senapati, U. (1998). Porcelain-raw materials, processing, phase evolution, and mechanical behavior. *Journal of the American Ceramic Society*, *81*(1), 3–20.

Casasola, R., Rincón, J. Ma., & Romero, M. (2012). Glass-ceramic glazes for ceramic tiles – a review. *Journal of Material Science, 47*, 553–582.

Chen, R., Li, Y., Xiang, R., & Li, S. (2016). Effect of particle size of fly ash on the properties of lightweight insulation materials. *Construction and Building Materials*, *123*, 120–126.

Chiang, Y. M., Birnie, D. P., & Kingery, W. D. (1997). *Physical Ceramics: Principle for ceramic science and engineering* (1st ed). Wiley-Interscience.

Coorstek. (2008). *Ceramic Properties Standard*. *Coorstek.Inc*. USA.

Dana, K., Das, S., & Das, S. K. (2004). Effect of substitution of fly ash for quartz in triaxial kaolin-quartz-feldspar system. *Journal of the European Ceramic Society, 24,* 3169–3175.

Dana, K., & Das, S. K. (2002). Some studies on ceramic body compositions for wall and floor tiles. *Transactions of the Indian Ceramic Society*, *61*(2), 83–86.

Dana, K., & Das, S. K. (2004). Evolution of microstructure in fly ash-containing porcelain body on heating at different temperatures. *Bulletin of Materials Science*, *27*(2), 183–188.

Dana, K., & Das, S. K. (2004). Partial substitution of feldspar by B.F. slag in triaxial porcelain: Phase and microstructural evolution. *Journal of the European Ceramic Society*, *24*, 3833–3839.

Dana, K., Dey, J., & Das, S. K. (2005). Synergistic effect of fly ash and blast furnace slag on the mechanical strength of traditional porcelain tiles. *Ceramics International*, *31*, 147–152.

Das, S. K., Dana, K., Singh, N., & Sarkar, R. (2005). Shrinkage and strength behaviour of quartzitic and kaolinitic clays in wall tile compositions, *29*, 137–143.

Das, S. K., Pal, M., Ghosh, J., Pathi, K. V., & Mondal, S. (2013). The effect of basic oxygen furnace slag and fly ash additions in triaxial porcelain composition: Phase and micro structural evolution. *Transactions of the Indian Institute of Metals*, *66*(3), 213–220.

De Jonghe, L. C., & Rahaman, M. N. (2003). *"Sintering of Ceramics," Handbook of Advanced Ceramics: Materials, Applications, Processing and Properties* (2003 ed, Vol. 1–2). USA: Elsevier Inc.

De Noni, A., Hotza, D., Cantavella Soler, V., & Sánchez Vilches, E. (2011). Influence of composition on mechanical behaviour of porcelain tile. Part III: Effect of the cooling rate of the firing cycle. *Materials Science and Engineering A*, *528*(9), 3330–3336.

De Noni, A., Hotza, D., Soler, V. C., & Vilches, E. S. (2010). Influence of composition on mechanical behaviour of porcelain tile. Part I: Microstructural characterization and developed phases after firing. *Materials Science and Engineering A*, *527*(7–8), 1730–1735.

Eksi, A. K., & Yuzbasioglu, A. H. (2007). Effect of sintering and pressing parameters on the densification of cold isostatically pressed Al and Fe powders. *Materials and Design*, *28*(4), 1364–1368.

Ersoy, B., Kavas, T., Evcin, A., Baspinar, S., Sariisik, A., & Dikimen, S. (2009). Production of fired ceramic materials from fly ash with whiteware additive. *Journal of Science*, 45–52.

Frischholz, P. (2004). *The Breviary Technical Ceramics*. German: Verband der Keramischen Industrie.

García-Ten, J., Saburit, A., Bernardo, E., & Colombo, P. (2012). Development of lightweight porcelain stoneware tiles using foaming agents. *Journal of the European Ceramic Society*, *32*(4), 745–752.

Gil, C., Chiva, L., Cerisuelo, E., Carda, J. B., & Chemistry, O. (2006). Study of porosity in porcelain. *Qualicer,* (1), 43–48.

Gouvêa, D., Kaneko, T. T., Kahn, H., Conceição, E. S., & Antoniassi, J. L. (2015). Using bone ash as an additive in porcelain sintering. *Ceramics International*, *41,* 487–496.

Guggenheim, S., & Martin, R. T. (1995). Definition of clay and clay mineral: Joint report of the AIPEA nomenclature and CMS nomenclature committees. *Clays and Clay Minerals*, *43*(2), 255–256.

Guiya, J. (2013). *Recycling of fire clay waste material in tri-axial composition.* National Institute of Technology Rourkela. Bachelor Degree Thesis.

Guzmán, Á., Delvasto, S., Quereda, M. F., & Sánchez, E. (2015). Valorization of rice straw waste: production of porcelain tiles. *Cerâmica*, *61*, 442–449.

He, Y., Cheng, W., & Cai, H. (2005). Characterization of a-cordierite glass-ceramics from fly ash. *Journal of Hazardous Materials*, *B 120*(1–3), 265–269.

Hojo, J. (2019). *Materials Chemistry of Ceramics.* Singapore: Springer.

Hsu, C. T., Chou, C. J., Huang, T. S., Hung, P. M., & Chen, C. N. (2017). The effect of firing shrinkage ratio of ceramics on thickness. *Journal of Interdisciplinary Mathematics*, *20*(3), 937–950.

Iqbal, Y., & Lee, W. E. (2000). Microstructural evolution in triaxial porcelain. *Journal of the American Ceramic Society*, *83*(12), 3121–3127.

Iqbal, Y. (2008). On the glassy phase in tri-axial porcelain bodies. *Journal of Pakistan Materials Society, 2*(2). 62–71.

Jamo, H. U. (2015). *Mechanical properties of ceramics tiles by replacement of quartz by RHA and POFA.* Universiti Tun Hussein Onn Malaysia. Ph.D Thesis.

Jamo, H. U., Noh, M. Z., & Ahmad, Z. A. (2014). Effects of palm oil fuel ash composition on the properties and morphology of porcelain-palm oil fuel ash composite. *Jurnal Teknologi (Sciences & Engineering), 70*(5), 5–10.

Khan, S. U., Nuruddin, M. F., Ayub, T., & Shafiq, N. (2014). Effects of different mineral admixtures on the properties of fresh concrete. *The Scientific World Journal*, *2014*, 1–11.

Kim, K. H., Yoon, S. Y., & Park, H. C. (2014). Recycling of coal fly ash for the fabrication of porous mullite/alumina composites. *Materials, 7*(8), 5982–5991.

Kim, K., Kim, K., & Hwang, J. (2015). LCD waste glass as a substitute for feldspar in the porcelain sanitary ware production. *Ceramics International*, *41*(5), 7097–7102.

Kingery, W. D., Bowen, H. K., & Uhlmann, D. R. (1976). *Introduction to ceramics* (2nd ed). Wiley-Interscience.

Kitouni, S., & Harabi, A. (2011). Sintering and mechanical properties of porcelains prepared from algerian raw materials. *Cerâmica*, *57*, 453–460.

Koca, Ç., Karakus, N., Toplan, N., & Toplan, H. Ö. (2012). Use of borosilicate glass waste as a fluxing agent in porcelain bodies. *Journal of Ceramic Processing Research*, *13*(6), 693–698.

Kovac, J., Trnik, A., Medved, I., Stubna, I., & Vozar, L. (2016). Influence of fly ash added to a ceramic body on its thermophysical properties. *Thermal Science, 20*(2), 603–612.

Kumar, S., Singh, K. K., & P. Ramachandrarao. (2001). Effects of fly ash additions on the mechanical and other properties of porcelainised stoneware tiles. *Journal of Materials Science*, *36*, 5917–5922.

Kumar, V., & Jha, C. N. (1999). *Fly ash for high value added applications*. India.

Lerdprom, W., Chinnam, R. K., Jayaseelan, D. D., & Lee, W. E. (2016). Porcelain production by direct sintering. *Journal of the European Ceramic Society, 36*(16), 4319–4325.

Lu, J., Lu, Z., Peng, C., Li, X., & Jiang, H. (2014). Influence of particle size on sinterability, crystallisation kinetics and flexural strength of wollastonite glass-ceramics from waste glass and fly ash. *Materials Chemistry and Physics*, *148*(1–2), 449–456.

Luo, Y., Ma, S., Liu, C., Zhao, Z., Zheng, S., & Wang, X. (2017). Effect of particle size and alkali activation on coal fly ash and their role in sintered ceramic tiles. *Journal of the European Ceramic Society*, *37*(4), 1847–1856.

Luo, Y., Zheng, S., Ma, S., Liu, C., & Wang, X. (2017). Ceramic tiles derived from coal fly ash: Preparation and mechanical characterization. *Ceramics International*, *43*, 11953–11966.

Martín-márquez, J., Rincón, J. M., & Romero, M. (2010). Effect of microstructure on mechanical properties of porcelain stoneware. *Journal of European Ceramics Society*, *30*, 3063–3069.

Martín-Márquez, J., Rincón, J. M., & Romero, M. (2008). Effect of firing temperature on sintering of porcelain stoneware tiles. *Ceramics Internacional*, *34*(8), 1867–1873.

Martín-Márquez, J., Rincón, J. M., & Romero, M. (2010). Mullite development on firing in porcelain stoneware bodies. *Journal of the European Ceramic Society*, *30*(7), 1599–1607.

Mathur, R., & Soni, A. (2013). Study on the particle size distribution (nano-particles) of mining minerals on whiteness of triaxial body. *International Journal of Modern Physics: Conference Series*, *22*, 239–247.

Monteiro, R. C. C., Mota, C. S., & Lima, M. M. A. R. (2004). Recycling of coal fly ash by ceramic processing. *International RILEM Conference on the Use of Recycled Materials in Buildings and Structures*, (March), 982–987.

Mukhopadhyay, T. K., Ghosh, S., Ghosh, J., Ghatak, S., & Maiti, H. S. (2010). Effect of fly ash on the physico-chemical and mechanical properties of a porcelain composition. *Ceramics International*, *36*(3), 1055–1062.

Mustafi, S., Ahsan, M., Dewan, A. H., Ahmed, S., Khatun, N., & Absar, N. (2011). Effect of waste glass powder on physico-mechanical properties of ceramic tiles. *Bangladesh Journal of Scientific Research*, *24*(2), 169–180.

Noh, M. Z., Jamo, H. U., & Ahmad, Z. A. (2014). Effect of temperature and composition of palm oil fuel ash on compressive strength of porcelain. *Applied Mechanics and Materials*, *660*, 173–177.

Noh, M. Z., Jamo, H. U., & Ahmad, Z. A. (2016). The hardness properties of porcelain with substitution of quartz by rice husk ash at different soaking time. *Materials Science Forum*, *840*(6), 39–43.

Ogundare, T., Fatile, O., & Ajayi, O. (2016). Development and characterization of parian bodies using feldspar from two selected deposits. *Leornado Electronic Journal of Practices and Technologies*, *4*(1), 147–156.

Ozturk, Z. B., & Ay, N. (2012). An investigation of the effect of alkaline oxides on porcelain tiles using factorial design. *Journal of Ceramic Processing Research*, *13*(5), 635–640.

Pal, M., & Das, S. K. (2017). Phase and microstructural evolution in quartz-free porcelain tile compositions. *Journal of the Australian Ceramic Society*, *54*(1), 109–117.

Papitha, R., Suresh, M., Rao, Y., Saha, B., Das, D., & Johnson, R. (2013). Pressure slip casting and cold isostatic pressing of aluminum titanate green ceramics: A comparative evaluation. *Processing and Application of Ceramics*, *7*(4), 159–166.

Pee, J., Kim, G., Kim, Y., Kim, J., & Punsukumtana, L. (2013). Development of Lightweight Pottery Using Organic and Inorganic Additives. *Suranaree Journal of Science and Technology* , *20*(2), 99–107.

Pee, J., Kobayashi, Y., Katayama, M., Kim, G., & Kim, Y. (2014). Preparation of lightweight porcelains using various types of pore-forming additives and their mechanical properties. *Journal of the Ceramic Society of Japan*, *122*(3), 204–210.

Predeanu, G., Volceanov, E., & Abagiu, T. A. (2007). Utilization of fly ash as a reuse material for ceramic industry. *Advances in Environment Technologies, Agriculture, Food and Animal Science*, *40*, 224–229.

Rajamannan, B., Sundaram, C. K., Viruthagiri, G., & Shanmugam, N. (2013). Effects of fly ash addition on the mechanical and other properties of. porcelainised stoneware tiles. *International Journal of Latest Research in Science and Technology*, *2*(1), 486–491.

Rasteiro, M. G., Gassman, T., Santos, R., & Antunes, E. (2007). Crystalline phase characterization of glass-ceramic glazes. *Ceramics International*, (33), 345–354.

Reed, J. S. (1995). *Principles of ceramics processing* (2nd ed, Vol. 83). New York: Wiley.

Riley, F. (2009). Structural Ceramics: *Fundamentals and Case Studies* (1st ed).

Cambridge University Press.

Romero, M., & Pérez, J. M. (2015). Relation between the microstructure and technological properties of porcelain stoneware. A review. *Materiales de Construcción, 65*(320), 1–16.

Majid, R. A., & Esa, H. (2017). The use of boiler fly ash for BOD, TSS and colour reduction of palm oil mill effluent. *Palm Oil Engineering Bulletin, 125,* 37–42.

Sánchez, E., García-Ten, J., Sanz, V., & Moreno, A. (2010). Porcelain tile: Almost 30 years of steady scientific-technological evolution. *Ceramics International*, *36*(3), 831–845.

Sedghi, A., Riahi-noori, N., Hamidnezhad, N., & Salmani, M. R. (2014). Effect of chemical composition and alumina content on structure and, *37*(2), 321–325.

Sembiring, S., Simanjuntak, W., Situmeang, R., Riyanto, A., & Karo-Karo, P. (2017). Effect of alumina addition on the phase transformation and crystallisation properties of refractory cordierite prepared from amorphous rice husk silica. *Journal of Asian Ceramic Societies*, *5*(2), 186–192.

Shackelford, J. F., & Doremus, R. H. (2008). *Ceramic and glass materials: Structure, properties and processing*. New York: Springer.

Sharma, A., Kabra, S., Katara, S., & A. Rani. (2015). Variation of surface morphology and physico-chemical properties of the fly ash through mechanical and thermal activations. *Journal of Advanced Chemical Sciences*, *1*(2), 70–74.

Siddiqui, A. R., Pal, M., Bhattacharya, D., & Das, S. K. (2014). Iron and steel slag: An alternative source of raw materials for porcelain ceramics. *Global Nest Journal*, *16*(4), 587–596.

Singer, F., & Singer, S. S. (1963). *Industrial Ceramics* (1st ed). Netherlands: Springer.

Snehesh, T. S. (2014). *Effect of some transition metal oxide additives on the fired of tri- axial ceramics*. National Institute of Technology, Rourkela. Ph.D Thesis.

Sokolář, R., & Šveda, M. (2016). The use of zeolite as fluxing agent for whitewares. *Procedia Engineering*, *151*, 229–235.

Souza, A. E., Teixeira, S. R., Santos, G. T. A., & Longo, E. (2013). Addition of sedimentary rock to kaolinitic clays: influence on sintering process. *Cerâmica*, *59*(349), 147–155.

Subasi, S. (2009). The effects of using fly ash on high strength lightweight concrete produced with expanded clay aggregate. *Scientific Research and Essay*, *4*(4), 275–288.

Sultana, M. S., Hossain, M. I., Rahman, A., & Khan, M. H. (2014). Influence of rice husk ash and fly ash on properties of red clay. *Journal of Scientific Research*, *6*(3), 421–430.

Sultana, P., Das, S., Bagchi, B., Bhattacharya, A., Basu, R., & Nandy, P. (2011). Effect of size of fly ash particle on enhancement of mullite content and glass formation. *Bulletin of Materials Science*, *34*(7), 1663–1670.

Tarhan, B., Tarhan, M., & Aydin, T. (2017). Reusing sanitaryware waste products in glazed porcelain tile production. *Ceramics International*, *43*(3), 3107–3112.

Tucci, A., Esposito, L., Rastelli, E., Palmonari, C., & Rambaldi, E. (2004). Use of soda-lime scrap-glass as a fluxing agent in a porcelain stoneware tile mix. *Journal of the European Ceramic Society*, *24*(1), 83–92.

Vernon, E. (2015). *Substitution of rice husk ash for quartz in ceramic wall tiles formulation*. Ahmadu Bello University Zaria Nigeria.

Wang, H., Zhu, M., Sun, Y., Ji, R., Liu, L., & Wang, X. (2017). Synthesis of a ceramic tile base based on high-alumina fly ash. *Construction and Building Materials*, *155*, 930–938.

Widodo, Solihin, & Subari. (2019). Effect of karangnunggal bentonite addition on the mechanical strength of conventional ceramics. *Indonesian Mining Journal*, *22*(1), 19–28.

Wunderlich, W. (2010). *Ceramic Materials* (2nd ed). Croatia: Sciyo.

Yap, S. P., Alengaram, U. J., Jumaat, M. Z., & Foong, K. Y. (2013). Waste materials in malaysia for development of sustainable concrete: A Review. *Electronic Journal of Structural Engineering*, *13*(1), 60–64.

Ye, H., Hou, J., Zhang, W., & Yao, S. (2013). Influence of sinter temperature on the hardness of fly ash based glass ceramics. *Applied Mechanics and Materials*, *357–360*, 578–581.

Yue, M., Yue, Q. Y., & Qi, Y. F. (2010). Effect of sintering temperature on the properties of sludge ceramics and fly-ash ceramics. *Advanced Materials Research*, *150–151*, 1068–1072.

Yürüyen, S., & Toplan, H. O. (2009). The sintering kinetics of porcelain bodies made from waste glass and fly ash. *Ceramics International*, *35*(6), 2427–2433.

Zakaria, Z., & Haron, H. (2014). Characterisation of local bone ash for bone china production. *Jurnal teknologi (Sciences & Engineering)*, *66*(1), 25–34.

Zarina, Y., Mustafa Al Bakri, A. M., Kamarudin, H., Nizar, I. K., & Rafiza, A. R.

(2013). Review on the various ash from palm oil waste as geopolymer material. *Reviews on Advanced Materials Science*, *34*(1), 37–43.

Zhang, P., Li, S. X., & Zhang, Z. F. (2011). General relationship between strength and hardness. *Materials Science and Engineering A*, *529*(1), 62–73.

Zhang, Y., Yang, Y., Li, W., & Ren, Y. (2014). Effect of Al_2O_3 addition on the flexural strength and light-transmission properties of bone china. *International Journal of Applied Ceramic Technology*, *12*(4), 875–884.

Zeng, L., Sun, H., Peng, T., & Zheng, W. (2019). The sintering kinetics and properties of sintered glass-ceramics from coal fly ash of different particle size. *Results in Physics*. *15*. 1–7.