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Effect of Quartz Replacement with Palm Oil Fuel Ash (POFA) for Triaxial Porcelain Composition of 50%: 40%: 10%

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ABSTRACT

Palm oil fuel ash (POFA) is a waste material disposed by the palm oil industries after palm oil shell, kernel and fiber are burnt in the industries for the process of electricity generation. Triaxial porcelain (50% clay, 40% feldspar and quartz 10%) was adopted for this research. Quartz was progressively replaced with POFA at 0%, 20%, 40%, 60%, 80% and 100% respectively. The samples were dry pressed and 91 MPa was used as a mould pressure with different sintering temperatures of 100 °C, 1150 °C and 1200 °C respectively. The result shows that, samples containing POFA yield higher mass loss and volume shrinkage at all the sintering temperature range. Meanwhile, lower densities were reported when quartz is replaced with POFA at 100% for the entire temperature range. The maximum compressive strength (125.42 MPA) was obtained at sintering temperature of 1100°C for 100% replacement of quartz with POFA. XRD studies revealed higher mullitization in the samples containing palm oil fuel ash.

Keywords*:* Porcelain, Quartz, POFA, Feldspar, Clay

1. INTRODUCTION

Porcelain has been characterized as one of the high performance ceramic material produced from triaxial porcelain composition of the ratio 50%: 25%: 25% (i.e., clay, feldspar and quartz respectively). This composition is coupled with other components to achieve the desired industrial formulation [1]. One of the outstanding scientific features of porcelain that attracted industries to use porcelain for different applications are its surface hardness, impermeability and high mechanical resistance [2]. Porcelain is characterized to be partially transparent with white porous ceramic material. Each porcelain component was designed to play a specific role in making the final product; the clay part plays its role in body forming where it provides the plasticity and helps in developing the mechanical strength and mullite development during processing and finally, during firing, it provides the crystalline phase [3]. At low temperature, feldspar developed a glassy phase, assisting in achieving nearly zero open porosity (< 0.5 %), reducing the level of closed porosity (< 10 %) and

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assisting the sintering process to be achieved. Whereas Quartz, on the other hand, as a result of its high melting point, helps in providing dimensional and thermal stability [4].

Countries like Malaysia and Indonesia planted Elaeis Guineensis (palm oil trees), an African native trees as ornamental plants that turn out nowadays to be commercial trees. In places like Asia, America and Nigeria, they were found abundantly [5]. One of the greatest challenges faced by the milling industries all over the world was the disposal and management of POFA. Indiscriminate disposal of palm oil fuel ash led to environmental pollution as POFA take long time to biodegrade, hence a need for proper production, utilization and disposal is inevitable [6].

Palm oil industries disposed palm oil fuel ash (POFA) as by-product. To generate electricity by the palm oil industries, palm fibers, shells and empty fruit were burnt in-house at 800 °C to 1000 °C. This led to heating the boiler and subsequently the generation of electricity. Thus, ash is produced in the process which is known as palm oil fuel ash (POFA) [5]. After Indonesia, Malaysia was declared to be the second largest global producer and exporter of palm oil [7]. According to the United States Department of Agriculture in 2017, approximately 64.5 tonnes of palm oil was produced globally. It is further reported that, Malaysia and Indonesia alone, produced around 80% of the world's palm oil [5]. Furthermore, only limited amount of POFA is used currently, whereas most of it is abandon in landfill and waterways. Accordingly, several environmental pollutions have been reported [6]. Waste usage, especially palm oil industries waste such as bottom ash (BA), fly ash (FA) and palm oil fuel ash (POFA) has been projected to be the only way forward to save the environment from degradation [8]. Research further revealed that, the usage of POFA can also improve the surface resistance, improve strength and reduce water permeability of concrete containing high amount of recycled concrete aggregates [9].

The main aim of this study is to investigate the influence of substitution of quartz with POFA and to study the effect of sintering temperatures on the physical and mechanical properties of porcelain.

2. MATERIALS AND METHODS

Porcelain compositions (clay, feldspar and quartz powder) were supplied by a local supplier, Maju Saintifik Sdn. Bhd. Palm oil fuel ash (POFA) was supplied by palm oil plantation in Kluang, Johor, Malaysia. The POFA is oven dried to remove the moisture and ground to obtain smaller size of < 50 μm. The dried POFA powder was treated with hydrochloric acid to enhance the silica content and remove unwanted materials. The triaxial porcelain composition of ratio 50%: 40%: 10% of clay, feldspar and quartz was used. A progressive replacement of quartz with POFA at 0%, 20%, 40%, 60%, 80% and 100% was used. 1 wt% of Polyvinyl alcohol (PVA) was added to the new composition and mixed homogeneously using Lab Korean Ball Mill machine at 250 rev/sec speed for 12 hours. The mixed porcelain powder is pressed at 91 MPA mould pressure and sintered at 1100 °C, 1150 °C and 1200 °C temperatures respectively for 2 hours soaking time. To identify the influence of quartz with waste ash (POFA) on the properties of porcelain (both physical and mechanical), x-ray fluorescence analysis, bulk density, compressive strength, scanning electron microscopy and x-ray diffraction analysis were used.

3. RESULTS AND DISCUSSION

3.1 X-Ray Fluorescence Analysis (XRF)

Table 1 shows the result of XRF analysis for the three porcelain components viz. clay, feldspar, quartz and POFA. Table 1 further reveals that, the main chemical composition is SiO_2 in all the three compounds and POFA, such as 99.40% for quartz, 72.70% feldspar, 69.30% clay and 66.91% for POFA. Meanwhile, the second major component is alumina that has 24.30% in clay, 16,40% in feldspar, 6.44% in POFA and 0.22 % in quartz. Table 1 shows the XRF for clay, feldspar, POFA and quartz respectively.

Table 1: The result of XRF analysis for clay, feldspar, quartz and POFA.

Chemical Composition	Content (%)												
	SiO_2	Al_2O_3	Fe_2O_3	CaO	K_2O	P_2O_5	MgO	SO_3	Na_2O	MnO	TiO_2	Cs_2O	LOI
Clay	69.30	24.30	0.27	-	2.44	-	-	-	-	-	0.27	0.10	0.36
Feldspar	72.70	16.40	0.40	0.50	2.42	-	-	-	6.87	0.29	-	0.10	0.32
Quartz	99.40	0.22	-	-	-	-	-	-	-	-	-	0.10	0.28
POFA	66.91	6.44	5.72	5.56	5.20	3.72	3.13	0.33	0.19	-	-	-	2.30

3.2 Physical Properties

The physical properties of the samples have been studied and presented in Figure 1(a), 1(b) and 1(c) respectively. The percentage of mass loss versus the percentage of replacement of quartz with POFA is presented in Figure 1(a). It is clear that, as the replacement of quartz with POFA, the mass loss steadily increases for all the 3 sintering temperatures. This indicated that, the incorporation of POFA has a potential of producing lightweight porcelain. Similarly, Figure 1(b) shows the percentage of volume shrinkage which slightly increased as the replacement of quartz with POFA increases from 0% to 100% due to the increment of mass loss. Samples that were sintered at 1100 °C recorded the lowest volume shrinkage compared to other sintering temperatures because the density was not significantly affected. Thus, as the sintering temperature increases, so the densification, as this sintering temperature yielded a porous microstructure. Samples that were sintered at 1200 °C recorded the highest shrinkage compared to other sintering temperatures leading to a denser structure. It is therefore worthy to note that, the volume shrinkage increased with subsequent increase in the replacement of quartz with POFA, which is due to the reaction of oxides in POFA such SiO_2 (53.82%), $Fe2O_3$ (4.54%) and CaO (4.24%), where the presence of these oxides influences the reduction of viscosity of the melted silica by acting as fluxing oxides. Consequently, the volume shrinkage of the finished product was therefore enhanced [8].

Similarly, Figure 1© shows that, the bulk density decreases evenly as different percentages of POFA replacement and at different sintering temperatures. The graph further reveals that, as the percentage of POFA increased, the bulk density also increases. Hence, it is pertinent to note that the lowest bulk density was achieved at the highest percentage of POFA replacement. The lowest bulk density (2.43 g/c3) at 100% of POFA replacement at all the sintering temperatures of 1100 °C, 1150 °C and 1200 °C respectively. This is owing to POFA agglomerated and crushed nature and its inability to roll over one another leading to the increased inter-particle friction. Although POFA possessed a pozzolanic behaviour which means it has high packing effects, the samples still consist of void that contributes to lower densities [9]. Figure 1(a), 1(b) and 1(c) shows the graph of mass loss, percentage of shrinkage and bulk density of porcelain against the composition of POFA at different sintering temperatures.

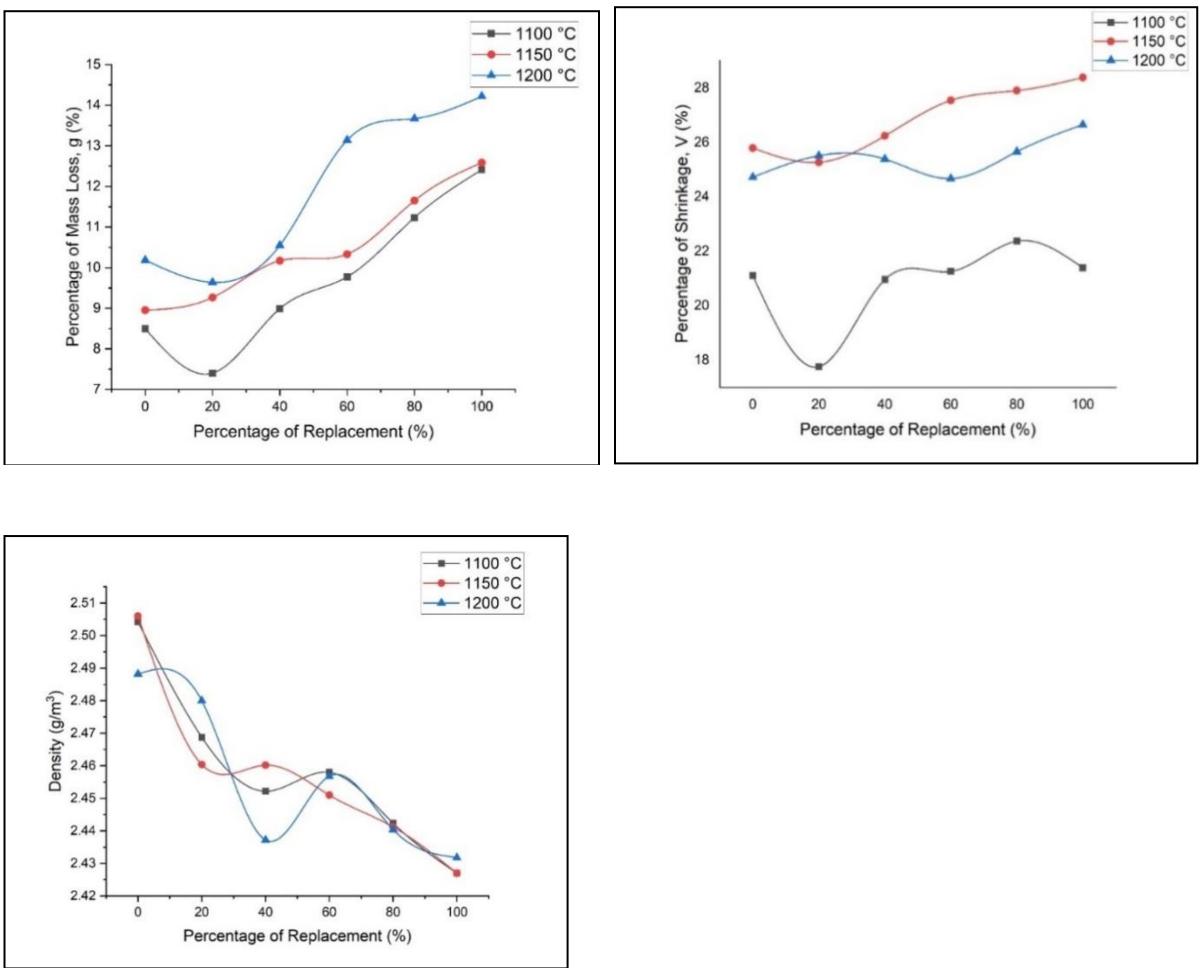

Figure 1. Graph of the (a) mass loss, (b) percentage of shrinkage, and (c) bulk density of porcelain against the composition of POFA at different sintering temperatures

3.3 Mechanical Properties

Researchers and industries considered compressive strength of porcelain to be the most important factor that determined the mechanical properties of porcelain. The result of compressive strength of this research is presented in Figure 2. It is indicated that, the compressive strength increases as the replacement increased at 1100 °C, that is from 92.05 MPa at 0% to 126.42 MPa at 100 %. The highest compressive strength for all the three sintering temperatures was obtained at 1100 °C which is 126.42 MPa at 100%. However, the lowest value of compressive strength for all the three sintering temperatures was obtained at 1200°C sintering temperature which is 31.03 MPa at 100% of the replacement. At higher temperatures, these compounds would initiate pores which subsequently reduced the strength of the final product [3]. As a result of matrix reinforcement, the presence of strengthening effect was noticed, therefore, it is worthy to note that it is difficult to identify the matching of the coefficient of the dispersed particles with that of the glass matrix in porcelain body. Similarly, the reinforcement of the matrix structure in the porcelain body was realised due to the replacement of quartz with palm oil fuel ash (POFA), whereas, the subsequent dissolution of quartz was influenced by the increase in sintering temperature, hence leading to the overall formation of matrix structure. It is also pertinent to note that, SiO_2 presence in meagre quantity facilitate the melting of other particles with the aid of feldspar [10]. Figure 2 shows the graph of compressive strength versus composition of palm oil fuel ash (POFA).

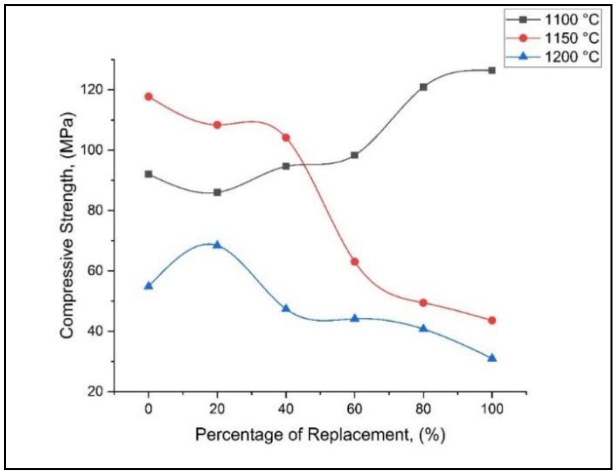

Figure 2. Graph of the compressive strength of porcelain against composition of palm oil fuel ash (POFA) at different sintering temperatures

3.4 X-Ray Diffraction (XRD)

Figure 3 shows the X-ray diffraction (XRD) pattern of the samples containing three different compositions of palm oil fuel ash (POFA); 0%, 40% and 100% with sintering temperature of 1100 °C. This sintering temperature was specifically selected to ascertain the reason behind maximum compressive strength on this temperature. From the figure, it is clear that, the mineralogical phases of the samples are visibly seen. Figure 3 further reveals quartz as the major identified phases and also mullite can easily be seen from the XRD analysis. The peak of quartz decreases as the percentage of POFA increases, and the formation of mullite increases as the quartz decreased. The percentage of mullite formed when 0%, 40% and 100% of POFA was replaced is 42.6%, 36.9% and 59.1% respectively, as reported by [13] where the mechanism behind the mullite growth was believed to be due to atmosphere induced changes to the composition in the oxidising atmosphere that facilitate mass transport and crystal growth. Therefore, when 100% of POFA was replaced, the highest compressive strength was achieved. The presence of SiO_2 and Al_2O_3 helped in mullitization of the crystal. The increment of the mullite is due to the melting of quartz grain which contributes to the formation of a homogeneous vitreous matrix [2]. According to Chaudhuri, mullite formation took place as a result of replacement of Al^{+3} in the porcelain structure owing to the role played by Fe^{+3} and Ti^{+4} that are refereed to foreign ions [3]. Since these foreign ions were found in the POFA, it helps in the formation of mullite as the percentage of POFA increases.

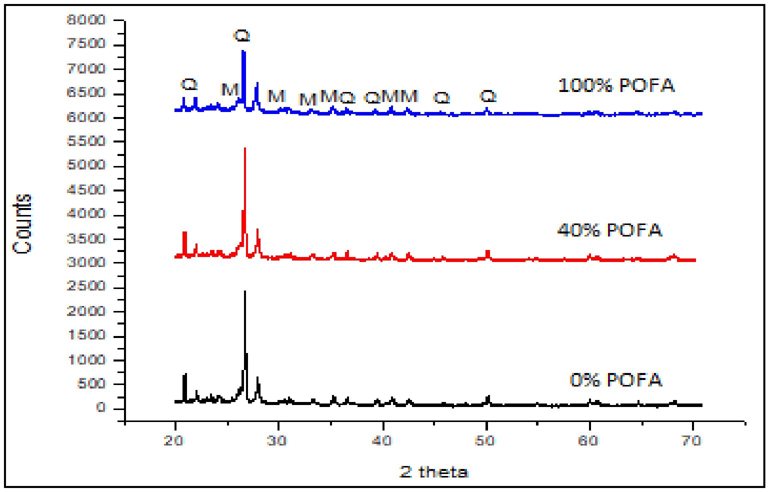

Figure 3. XRD pattern of three compositions of POFA replacement at sintering temperature of 1100°C

3.5 Microstructural Study

The microstructural study of the samples has been analysed by using Scanning Electron Microscope (SEM). Figure 4 shows that at 0% of POFA replacement, as indicated in Figure 4 (a), the sample has the lowest porosity and hole around the surface due to the absence of POFA. In Figure 4 (b) and 4 (c), for 60% and 80% of POFA replacement, more porosity and hole around the surface due to the addition of POFA is pronounce.

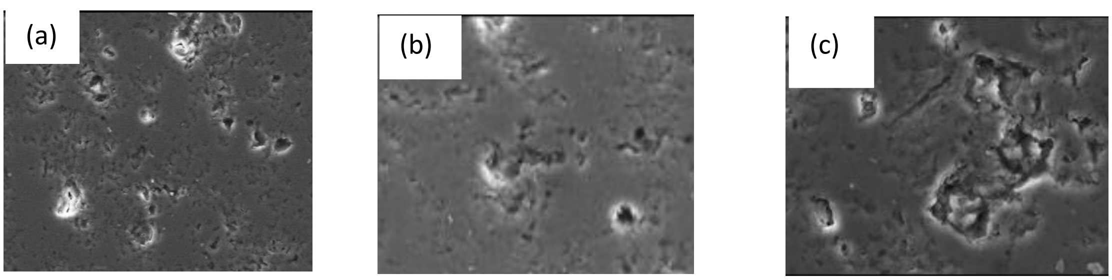

Figure 4 Micrograph of SEM of the sample sintered at 1100°C replacement at (a) 0%, (b) 60%, and (c) 80%

4. CONCLUSIONS

Effect of quartz replacement with POFA has been studied at different compositions and sintering temperatures. It is clear from the result that, at 100 % replacement of quartz with palm oil fuel ash (POFA), the maximum mass loss and volume shrinkage were achieved. Whereas, at 0 % replacement with 100 °C sintering temperature, the highest bulk density and compressive strength were realised as 2.55 g/cm^3 and 126 MPa respectively. The result also indicated that more quartz is substituted with POFA, the composition of SiO_2 decreases but the level of other compositions such as alumina, Fe_2O_3, CaO, K_2O, P_2O_5, MgO, SO_3, and Na_2O increases. The reaction between SiO_2 and Al_2O_3 form primary mullite during the sintering process. The formation of mullite can strengthen the mechanical properties of porcelain. Thus, from the microstructural analysis, it can be seen that POFA replacement with quartz yields a less porous and denser product, thus POFA can be used as quartz replacement.

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