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Developed Formulation Model by the Addition of SiO_2 for Optimum Physicomechanical Properties of Porcelain using Modified Palm Oil Fuel Ash (POFA)

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ABSTRACT

Palm oil industries disposed of palm oil fuel ash (POFA) as waste by-products and it is used to produce biodiesel. Porcelain is characterized as translucence and vitreous material sintered at a high temperature which consists of clay (for plasticity), feldspar (as flux) and quartz (filler). This research aims to investigate the effect of SiO_2 addition on porcelain production and develop a regression model for optimum physicomechanical properties of porcelain. POFA is dried in an oven, grind and sieved for particle size < 50 µm, the powder is substituted with quartz at 15 wt.% mixed with other compositions of porcelain grind homogeneously in a ball mill and SiO_2 is added to the composition at 1, 2, 3, 4, 5, 10 and 15 wt.% dry pressed into pallets at 91 MPa and sintered at 1150 °C. Physical and mechanical properties of porcelain were determined and a polynomial regression analysis model was developed to predict optimum physicomechanical properties of porcelain. It is revealed that the developed model shows an approximately similar value of bulk density, compressive strength and Vickers microhardness with the laboratory value.

Keywords: POFA, Porcelain, SiO_2, Regression and Polynomial Analysis.

1. INTRODUCTION

Palm oil fuel ash (POFA) is an agricultural waste product that is abundant in many countries of the tropical region. Its abundance and reckless disposal have attracted the attention of researchers around the globe focusing on the potentials of POFA [1]. This agricultural by-product is a result of burning palm oil shell, fibre, empty fruit bunch and kernel at a temperature between 800 °C -1000 °C to heat the boiler and generated electricity [2]. Due to the chemical composition of POFA, which constitute mainly silica, it can be used as pozzolanic material thus, researchers proposed its usage as a replacement of Portland cement in concrete. It is proven that the use of POFA as cement replacement reduce porosity that lead to the improvement in the durability of concrete (due to calcium hydroxide reduction in the cement matrix), enhanced resistance to chloride penetration and sulphate attack [1].

Recently, POFA receives attention in the ceramic industry due to its chemical properties that are similar to quartz. Research on the effect of substitution of quartz with POFA indicated that by replacing quartz with POFA at 15 wt.%, the compressive strength is reported to increase and it is attributed to the development of mullite along with the liquid phase [3].

Standard porcelain is also known as triaxial porcelain consist of 50% of clay (for plasticity), 25% of feldspar (as fluxing agent) and 25% of quartz (as filler). Due to the diverse applications of porcelain, it remains as the most extensively studied ceramic material. Porcelain has several applications from insulators, stoneware to whiteware [4]. Porcelain final product has been studied for several years in the ceramic industry, therefore each of the porcelain compositions plays a specific role. For an adequate amount of glassy phase, a specific amount of feldspar is required. To reduce the tendency of porcelain body to distortion and warp during sintering and to decrease volume shrinkage, a significant quantity of quartz is necessary. Similarly, clay provides plasticity for the body [5].

In order to obtain the desired porcelain specification, kinetics of firing, processing stages and influence of the raw materials are the most intricate parameters that have to be considered [6]. Physical and mechanical properties of porcelain such as water absorption, porosity, bulk density, compressive strength, volume shrinkage and microhardness depend on the microstructure of porcelain [7].

Production of porcelain has been the best product that evolved from the ceramic industry. Porcelain is a result of careful industrial research and sequence of preliminary work such as preparation of slip, mixing, drying of the slip and grinding of the raw material [8]. Lack of controlled procedure leads to technological deficiency in the final product such as grooves, scratches, subsurface cracks and material detachment [9].
Polynomial regression analysis is a procedure to develop a statistical model that explains the effect of a single independent variable X on the dependent variable Y. After running the test to determine the order of the polynomial, the one with the powers of X and its square is the best model to develop an estimation/prediction model [10]. Rheodes [11] reported that, polynomial regression analysis as an advanced statistical approach used in different field of research to determine how two predictors variables relate to the outcome variable.

This paper reported the result of the addition of modified POFA (SiO_2) on the physical and mechanical properties of porcelain and developed a prediction model using regression analysis for the optimum physicomechanical properties of porcelain.

2. MATERIAL AND METHOD

Palm oil fuel ash (POFA) was dried in an oven at 110 °C for 24 hours to remove the moisture content and then grind in a ball mill machine at a speed of 250 rev/sec for particle size <50 μm. Triaxial porcelain of 50% clay, 25% feldspar and 25% quartz were adopted in this research. POFA powder was substituted with quartz at 15 wt.% and mixed homogeneously in a ball mill for 12 hours. Modified POFA (SiO_2) was also added to the mixture at 1, 2, 3, 4, 5, 10 and 15 wt.% of POFA mixed and dry pressed into pallet at mould pressure 91 MPa and then sintered at a temperature of 1150 °C. To check the effect of modified POFA (SiO_2) on physical and mechanical properties of porcelain, X-ray fluorescence analysis (XRF), X-ray diffraction analysis (XRD), bulk density, compressive strength and Vickers microhardness were adopted. Polynomial regression analysis was used to develop the prediction model for optimum physicomechanical properties of porcelain.

3. RESULTS AND DISCUSSION

To check the chemical composition of palm oil fuel ash (POFA), Bruker S4 Pioneer X-ray fluorescence analysis operated at 60 kVp and 50 mA is used, and the result is presented in Table 1. The result of the chemical analysis indicated that SiO_2 is the major composition then

followed by K_2O, CaO and P_2O_5. It is also evident that the content of carbon which is 0.1 wt.% is within the limit of standard porcelain (1.5 wt.%) [12].

Table 1 Chemical composition of POFA

Compound	SiO_2	C	K_2O	CaO	P_2O_5	Al_2O_3	Fe_2O_3	MgO	SO_3	Cl	TiO_2
Composition	43.2	0.1	8.62	7.75	3.81	2.68	2.65	2.42	1.14	0.95	0.27

Table 1 indicates the presence of alkaline earth elements such as Mg, Ca and K, where during sintering, they act as flux which helps in porosity reduction and subsequent densification of porcelain [13]. It is therefore important to note that POFA has a similar chemical composition with quartz due to high silica content and thus can be used as quartz replacement to produce porcelain.

X-ray diffraction analysis (XRD) was used to determine the intensity and phases of the porcelain sample. In order to calculate the incident ray and diffracted ray as an angle, XRD machine was set at Cu-kα with scanning rate 0.05 °/second at $10° \geq 2\theta \leq 90°$. Figure 2 shows the XRD pattern of the sample.

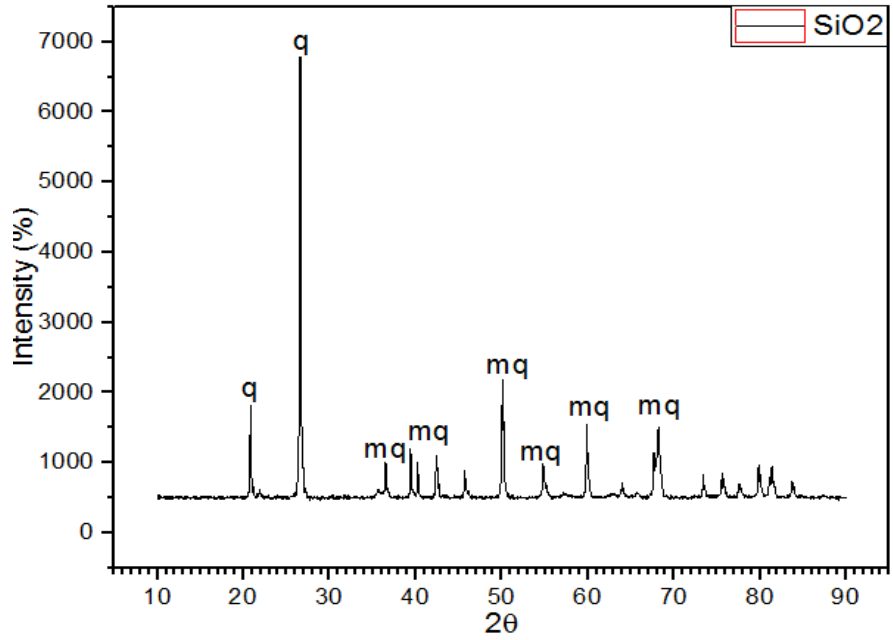

Figure 1. X-ray diffraction analysis of porcelain with addition of SiO_2 (q = quartz and mq = magnesium silicate).

XRD analysis shows that after the addition of SiO_2 to the composition of porcelain, the peak of quartz crystallized, and the dominant compound is quartz and then magnesium silicate which is also another form of SiO_2.

Figure 2 shows the apparent porosity and volume shrinkage of porcelain after addition of SiO_2 at 1, 2, 3, 4, 5, 10 and 15 wt.%. It is revealed that apparent porosity decrease with the increase in the addition of SiO_2, at 5 wt.% the minimum value was achieved. Whereas, at 10 and 15 wt.% the values increase again, this shows that at 5 wt..% there is evidence of complete densification [12]. It was reported that the reduction of porosity is due incorporation of waste ash that results in glassy phase formation [14] whereas, [15] describe the behaviour as a result of glass formation on the surface due to industrial ash addition such as POFA. Similarly, volume shrinkage decreases evenly with the increase in the composition of SiO_2, with approximately 12% at 5 wt.% composition, but at 10 wt.% the value abruptly increase and then go down again

to the lowest value at 15 wt.%. This indicates that the nature of POFA affect the volume shrinkage. Nevertheless, the value at 5 wt.% is similar to the standard porcelain obtain by [16], thus, the researcher pronounced that the lower the volume shrinkage the better mechanical strength of porcelain.

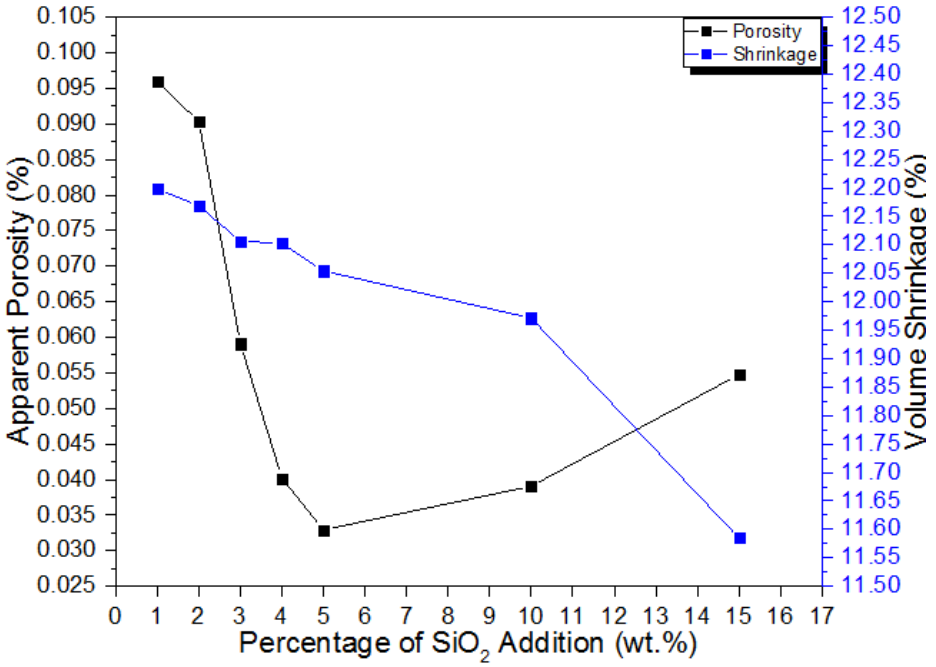

Figure 2. Apparent porosity and volume shrinkage of porcelain with the addition of SiO_2.

The variation of bulk density versus composition of SiO_2 is plotted and presented in Figure 3. It is pertinent to note that, bulk density increased with the increase in the composition of SiO_2. The maximum bulk density was attained at 5 wt.% composition after which a drastic decrease was noted at 10 and 15 wt.%. Addition of excess SiO_2 lead to the formation of a less viscous glass surface that negatively affects the bulk density. Tonnayopas reported that above 1100 °C transformation and recrystallization of quartz take place that resulted in excess glass formation and subsequent decrease in bulk density [17]. Similarly, Ghazal also agreed that the decrease in bulk density is related to the increase in densification and excess addition of POFA and in this case, SiO_2. The more composition of SiO_2, the more glassy of the surface and compaction, hence, decreased the bulk density [18]. Mass loss can be described as the difference of mass between the green pallets and the sintered porcelain sample. Figure 3 shows the percentage of mass loss against the composition of SiO_2, therefore, it is clear that the maximum mass loss was obtained at 5 wt.% after that the value drop at 10 and 15 wt.% respectively. Kitouni and Harabi attributed the reduction in mass loss to the formation of solid bonds between the particles that reduce the mass of the porcelain samples [5][23].

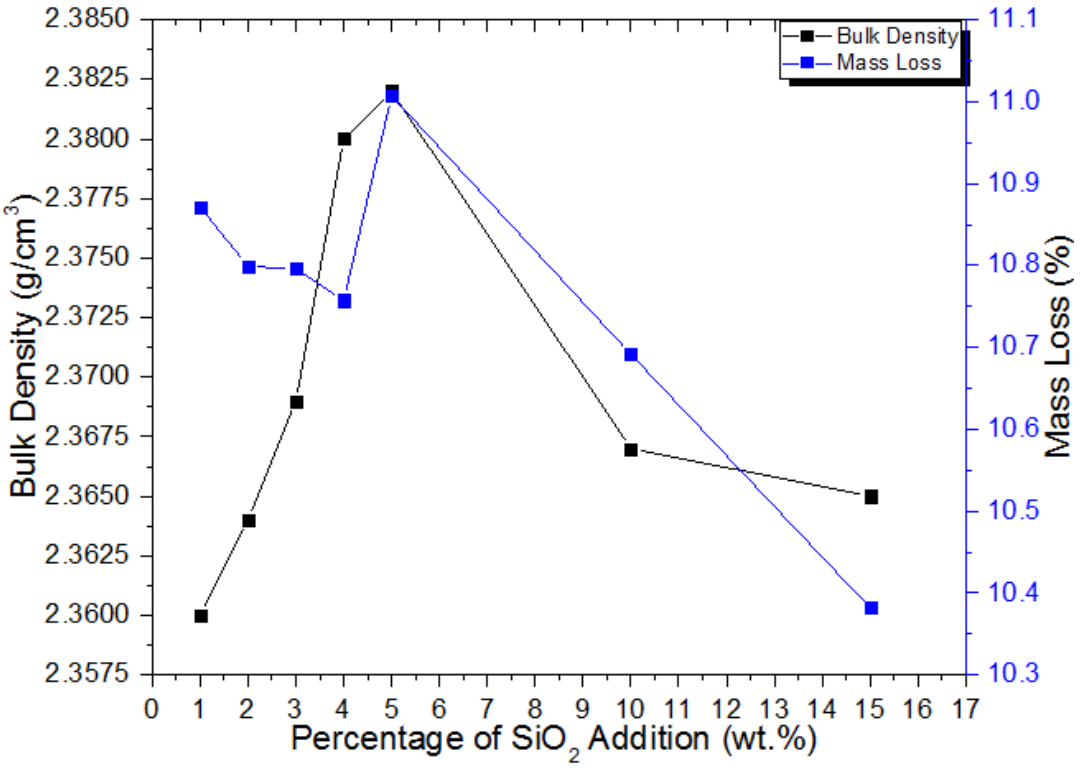

Figure 3. Bulk density and mass loss of porcelain with the addition of SiO_2.

To determine the compressive strength and Vickers microhardness of the porcelain sample after addition of SiO_2, universal testing machine (UTM) and Shimadzu HMV-2 series were used. Figure 4 shows the compressive strength and Vickers microhardness of porcelain. Based on the pattern in Figure 4, it is clear that SiO_2 addition plays a vital role in altering the compressive strength of porcelain. The maximum value was attained at 5 and 15 wt.% which is 132.12 and 133.06 MPa, respectively. Noteworthy, as the composition of SiO_2 increased, the compressive strength also increases until reaching maximum and then start decreasing which could be attributed to the reinforcement of the matrix and subsequent dissolution of quartz particles. Jamo revealed that SiO_2 and addition of POFA enrich matrix reinforcement by dissolving particles in the porcelain. The researcher further argues that the decrease of compressive strength is related to the porosity development and subsequent decrease in bulk density [19]. Researchers like Mukhopadhyay reported that due to the viscosity of the liquid phase and amount of liquid phase in the sample during sintering, the strength of porcelain decrease as the percentage of porosity increased [12][22].

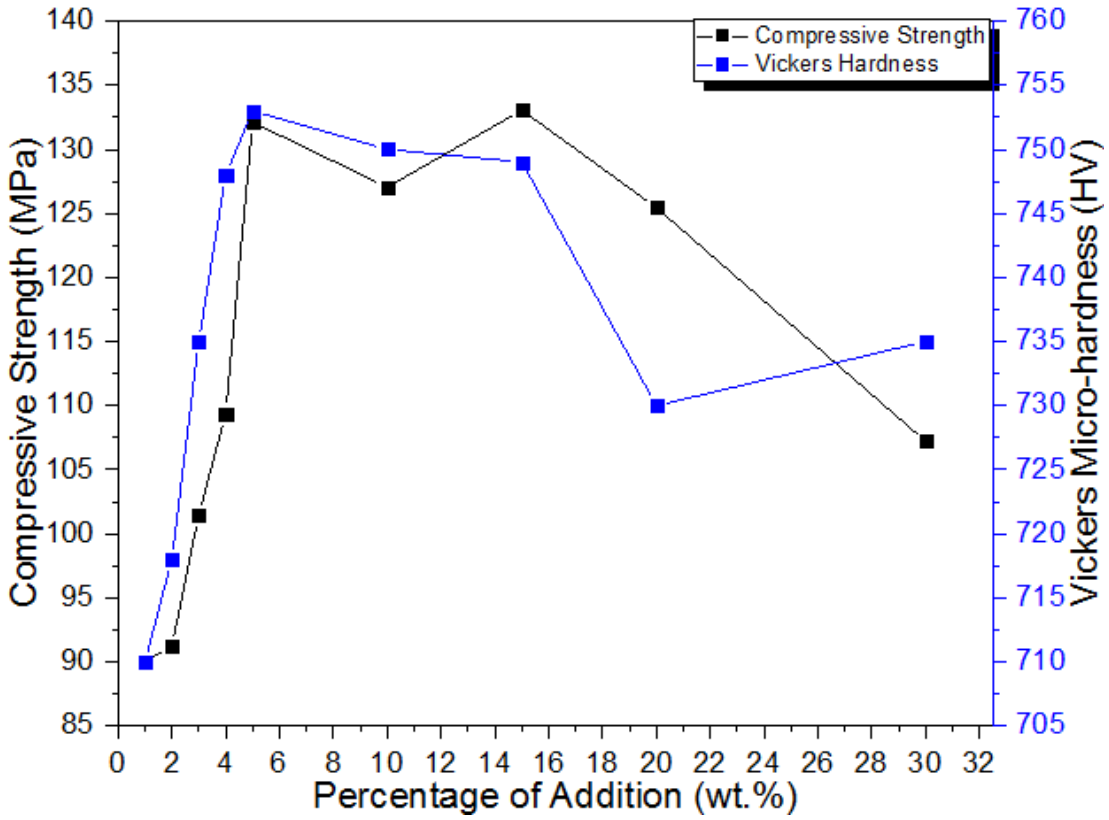

Figure 4. Compressive strength and Vickers microhardness of porcelain by addition of SiO_2.

Similarly, Vickers microhardness is very important in determining the mechanical properties of porcelain. Figure 4 indicates a similar trend for Vickers microhardness and compressive strength. The maximum hardness was recorded at 5 wt.% as 753 HV. After a steady increase from 1 to 5 wt.%, the value progressively decreases; this pattern is related to porosity removal through infusion and vitrification of the sample due to addition of SiO_2 [21]. Kitouni and Harabi attributed the increase in Vickers microhardness to the lower porosity and densification. Whereas Jamo, Youssef and Ghazal concluded that the pattern is due to the reduction of bulk density and porosity. The conclusion by Jamo et al. is also supported by Figure 2 and Figure 3 [19][20].

Regression analysis is a tool in statistical modelling for estimation and prediction of relationships. Polynomial regression analysis is used to develop a model for prediction/estimation of optimum physicomechanical properties of porcelain and the polynomial model and developed models are presented below.

$$Y = \beta o + \beta 1xi + \beta 2xi2 + \beta 3xi3 + \ldots \beta ixi + \varepsilon \quad (1)$$

Where,

Y is the dependent variable
Xi is the independent variable (i = 1,2…, k)
βi is the model parameter (i = 1,2…, k)
ε is the random error of the model

Therefore, Figure 5 shows the developed polynomial model for the prediction and estimation of physicomechanical properties of porcelain. Hence, to obtain a prediction/estimation model, Equation (1) and Figure 5 were used to develop a modified model for the estimation/prediction

of optimum physicomechanical properties of porcelain using polynomial regression analysis and the result is presented in Table 2.

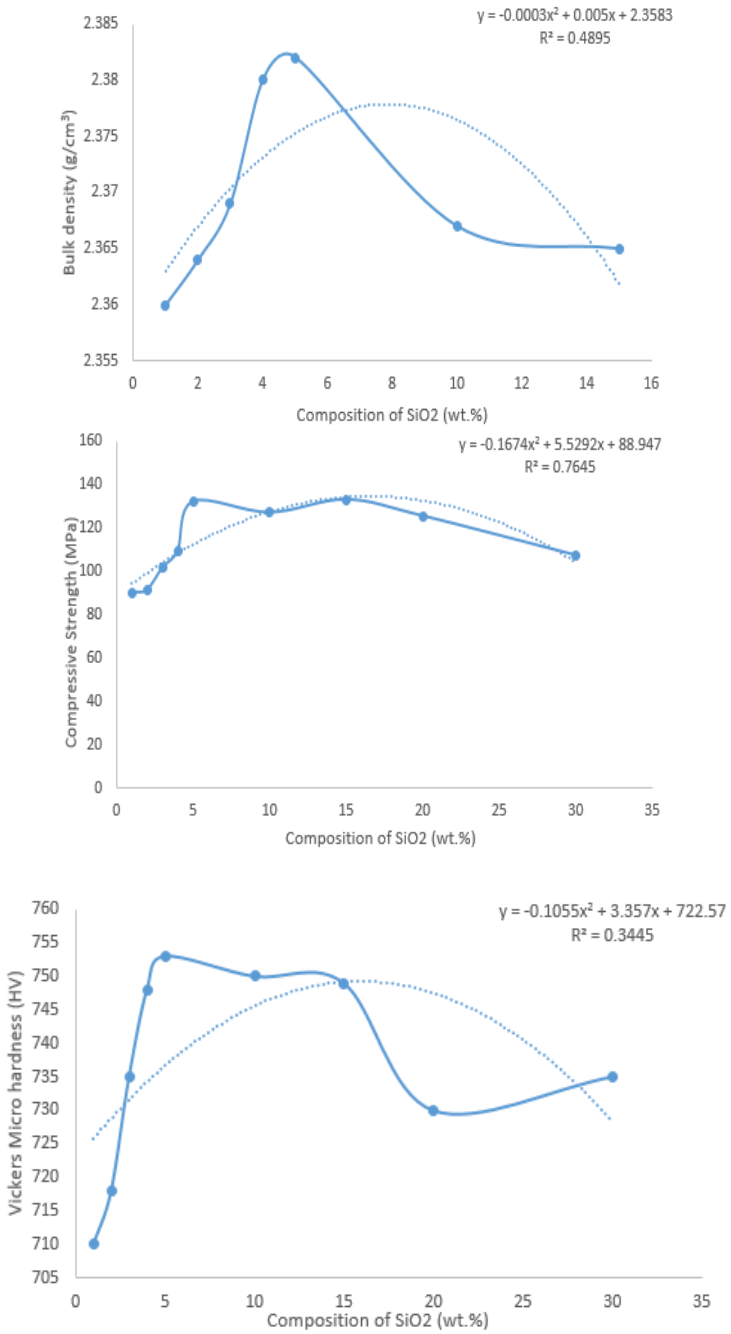

Figure 5. Developed regression analysis models for bulk density, compressive strength, and Vickers microhardness.

Table 2. Developed models for bulk density, compressive strength, and Vickers hardness.

S/N	Models for	Developed models
1	Bulk density	$y = -0.0003x^2 + 0.005x + 2.3583$ and $R^2 = 0.4895$
2	Comp. strength	$y = -0.1674x^2 + 5.5294x + 88.957$ and $R^2 = 0.7645$
3	Vickers Micro H.	$y = -0.1055x^2 + 3.357x + 722.57$ and $R^2 = 0.3445$

Conclusively, Table 2 was used to determine the predicted/estimated values for bulk density, compressive strength, and Vickers microhardness and the result is presented in Table 3. From Table 3, it is recognized that the predicted models and laboratory values were approximately the same. Furthermore, the model result revealed that the prediction is viable. Table 3 shows the predicted/estimated values for bulk density, compressive strength, and Vickers microhardness.

Table 3 Predicted bulk density, compressive strength, and Vickers microhardness using polynomial regression analysis

Composition of SiO_2 (wt.%)	Bulk density (g/cm^3)	Compressive strength (MPa)	Vickers microhardness (HV)
1	2.363	94.3088	725.8215
2	2.3671	99.3358	728.862
3	2.3706	104.028	731.6915
4	2.3735	108.3854	734.31
5	2.3758	112.408	736.7175
10	2.3783	127.499	745.59
15	2.3658	134.22	749.1875

The laboratory values for bulk density, compressive strength and Vickers microhardness are presented in Table 4 below.

Table 4 Laboratory values of bulk density, compressive strength and Vickers microhardness

Composition of SiO_2 (wt.%)	Bulk density (g/cm^3)	Compressive strength (MPa)	Vickers microhardness (HV)
1	2.360	90.02	710
2	2.364	91.22	718
3	2.369	101.46	735
4	2.380	109.39	748
5	2.382	132.12	753
10	2.367	127.06	750
15	2.365	133.06	749

4. CONCLUSIONS

Effect of substituting palm oil fuel ash (POFA) and addition of SiO_2 to the composition of porcelain is determined and the result indicates that SiO_2 plays a vital role in the production of porcelain. The maximum bulk density, compressive strength and Vickers microhardness was found to be 2.382 g/cm^3 at 5 wt.%, 133 MPa 15 wt.% and 753 HV 5 wt.% respectively. A polynomial model was developed for prediction of optimum physicomechanical properties of porcelain and the result agrees with the result from the laboratory test. Thus, the developed model is declared to be viable for this research using the same compositions.

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REFERENCE

[1] P. Chindaprasirt, S. Rukzon, & V. Sirivivatnanon, "Resistance to chloride penetration of blended Portland cement mortar containing palm oil fuel ash, rice husk ash and fly ash," Constr. Build. Mater., **22**, 5 (2008) 932–938.
[2] S. Rukzon & P. Chindaprasirt, "An Experimental Investigation of the Carbonation of Blended Portland Cement Palm Oil Fuel Ash Mortar in an Indoor Environment," Indoor Built Environ. **18**, 313–318 (2009).
[3] H. U. Jamo, M. Z. Noh, & Z. A. Ahmad, "Effects of Mould Pressure and Substitution of Quartz by Palm Oil Fuel Ash on Compressive Strength of Porcelain," **087** (2015) 21–125.
[4] S. L. Correia, "Properties of Triaxial Porcelain Bodies: Interpretation of Statistical Modeling," **3365** (2006) 3356–3365, 2006.
[5] S. Kitouni & A. Harabi, "Sintering and mechanical properties of porcelains prepared from Algerian raw materials," **57** (2011) 453–460, 2011.
[6] J. Martín-Márquez, J. M. Rincón, & M. Romero, "Effect of firing temperature on sintering of porcelain stoneware tiles," Ceram. Int., **34**, 8 (2008) 1867–1873.
[7] F. Güngör & N. Ay, "The effect of particle size of body components on the processing parameters of semi-transparent porcelain," Ceram. Int., no. November 2017, 2018.
[8] L. Esposito, A. Tucci, & D. Naldi, "The reliability of polished porcelain stoneware tiles," J. Eur. Ceram. Soc., **25**, 2005 (2004) 1487–1498.
[9] R. W. Rice, "Monolithic and composite ceramic machining flaw-microstructure-strength effects: model evaluation," J. Eur. Ceram. Soc. **22** (2002) 1411–1424.
[10] S. Point, "Polynomial Regression Analysis," StartPoint Technol. Inc. **7,** 7 (2009) 1–20.
[11] L. Rhoades, S. Benjamin, & E. D. Heggestad, "Polynomial Regression with Response Surface Analysis: A Powerful Approach for Examining Moderation and Overcoming Limitations of Difference Scores," J. Bussines Psychol. **25** (2010) 543–554.
[12] T. K. Mukhopadhyay, S. Ghosh, J. Ghosh, S. Ghatak, & H. S. Maiti, "Effect of fly ash on the physico-chemical and mechanical properties of a porcelain composition," Ceram. Int. **36**, 3 (2010) 1055–1062.
[13] M. Dal, L. Dominguini, A. Zimmer, S. R. Grando, P. Kaspari, & D. Hotza, "Chemical tempering of porcelain tiles," Ceram. Int. **42**, 14 (2016) 15199–15202.
[14] K. Dana, S. Das, & D. S. Kumar, "Effect of Substitution of Fly Ash for Quartz in Triaxial Kaolin – Quartz – Feldspar System kaolin – quartz – feldspar system," J. Eur. Ceram. Soc., **24** (2004) 3169–3175.
[15] S. Yürüyen & H. O. Toplan, "The sintering kinetics of porcelain bodies made from waste glass and fly ash," Ceram. Int. **35**, 6 (2009) 2427–2433.
[16] C. Prasad, K. Maiti, & R. Venugopal, "Effect of Rice Husk Ash in Whiteware Compositions," Ceram. Int. **27**, 6 (2001) 629–635.
[17] D. Tonnayopas & P. Tekasakul, "Effects of Rice Husk Ash on Characteristics of Lightweight Clay Brick," in Technology and Innovation for Sustainable Development Conference (TISD2008), 2014, no. January 2008, 36–39.
[18] K. Galos, "Applied Clay Science Composition and ceramic properties of ball clays for porcelain stoneware tiles manufacture in Poland," Appl. Clay Sci. **51**, 1–2 (2011) 74–85.
[19] H. U. Jamo, "Mechanical Properties of Ceramic Tiles by Replacement of Quartz by RHA and POFA," (2015).

[20] M. M. Youssef & H. B. G. Ghazal, "Characterization and Reuse of Kiln Rollers Waste in the Manufacture of Ceramic Floor Tiles," J. Am. Sci. **7**, 5 703–709.
[21] F. H., Saeed & K. K. San'a, Theoretical model for temperature distribution resulting from CW-Laser radiation heats up tumor tissues, (2019).
[22] Z. I. Taka, Mohd Kamarulzaki, M., A. S. Khairunnadim, & Saliza, A. Ultrasonic Assisted Preparation and Characterization of Conductive Polyaniline-Modified Magnetite Nanocomposites (PAni/Fe3O4 Nanocomposites), (2019).
[23] S. A. A. Anaam, Hashim, S., Mohd Zainizan, S., & Al-Gheethi, A. Defective TiO2 with intrinsic point defects for photocatalytic hydrogen production: A review, (2019).