Optimizing ternary-blended geopolymerswith statistical multi-response surface analysis

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Abstract

Geopolymershavebeen recently gaining attention as an alternative binder for concrete because of its potential to lower the environmental impact of construction, to utilize waste as raw materials of alumino-silicates, and to enhance the material performance. In this study, engineering properties of lightweight geopolymer-based material produced from the ternary blend of red mud (RM) waste, rice husk ash (RHA) and diatomaceous earth (DE)are optimized with statistical multi-response surface method. Using the augmented simplex lattice mixture design, ten mix proportions of RM, RHA and DE were prepared and mixed with 15% (by weight of the solid) water glass solution to produce the specimens. After 28 days of curing at room temperature, these specimens were tested for compressive strength (MPa), volumetric weight (kg/m^3), and water absorption (kg/m^3) including the mass loss (%), volumetric shrinkage (%) and change in compressive strength (%)when subjected to an elevated temperature of 1000^{0}C. By using the desirability function approach on multiple responses, theoptimum ternary blend was found to be14.49% RM, 67.17% RHA and 18.34% DEto obtain the desirable engineering properties of a lightweight heat resistant material. Using thismix proportion,confirmatoryrunswere also done and the experimental valueswere found to be in good agreementwith the predicted values.

Keywords: geopolymer, multiple response surface method, desirability function, red mud, rice husk ash, diatomaceous earth

1. Introduction

Concrete is the most ubiquitous construction material throughout the world, and concrete made from Portland cement binder is also considered second to freshwater as the most widely used commodity (Aitcin 2000; Bentur 2002). Large volume of cement is thus being produced globally (e.g., an estimated 5.5 billion tons in 2030 (Worrell et al. 2009)), and these cement and concrete industries are expected to expand significantly with the rapidly increasing demand for civil infrastructure in China, India, the Middle East, and other developing nations (Taylor, et al,

2006;Hasanbeigi et al. 2013;Mahasenan et al. 2003). However, the environmental footprint and energy intensity associated with these cement-based materials have been recognized as an alarming issue toward the development of sustainable infrastructure in a carbon-constrained society.For example, cement plants have emitted about two billion tonnes of CO_2 per year (which is around5-7% of the global anthropogenic CO_2) including emissions of harmfulparticulates(Damtoft et al. 2008; Shi et al. 2011;Ogunkunle and Fatoba 2013). Cement production is also considered as one of the energy-intensive industries andconsumes around 4 to 5.6 GJ per tonne of cement clinker produced (Worrell et al. 2000; CIPEC 2001).Sustainable solutions such as emission sequestration, waste utilization in cement production, pozzolan blended cements in producing concrete, and among others (Koji Sakai 2005; Phair 2006; Nielsen and Glavind 2007) are thus being sought to reduce the CO_2 footprint and energy burden of Portland cement-based concrete without sacrificing its economic viability.Another approach also being considered is to find an alternative binder or cementitiousmaterial which does not use Portland cement at all (Shi et al. 2011; Juenger et al. 2011; Sadique and Al-Nageim 2012;Petermann et al. 2010).

Geopolymer has been recently gaining attention as an alternative binder for Ordinary Portland cement (OPC) due to its low energy and CO_2 burden (Davidovits 1994, 2002).Geopolymer, the term originally coined by Davidovits in the 1970s, is a kind of inorganic polymer formed from the reaction of alkaline solution withmaterials rich in reactive silica and alumina (Davidovits1994,2011). This binder is also referred by other researchers as alkali-activated pozzolan cements (Shi et al.2011) to describe the alkali activation of the solid alumino-silicate raw materials in a strongly alkaline environment. The solid is typically mixed with highly alkaline liquid (e.g., alkali silicates and/or hydroxides solution) to produce a resulting paste that can set and harden like a Portland cement.It has been estimated that the use of such geopolymer cement can reduce about 80% of the CO_2 emissions associated with the cement production (Van Deventer et al.2012). In addition, its reported advantage over OPC in terms of material performance includes longer life and durability, higher heat and fire resistance, and better resistance against chemical attack (Bakharev 2005; Kong and Sanjayan 2010;Davidovits 2011, Petermann et al. 2010).Unlike Portland cement, the solid component of such binder, which is the main source of reactive aluminosilicates, can be sourced out entirely from industrial waste materials such as blast furnace slag, fly ash, bottom ash, rice husk ash,and red mud (Xu et al.2003; Kumar et al. 2007; Dimas et al. 2009; Zhang and He 2011; Petermann et al. 2010; Juenger et al. 2011).

This paper presents the utilization ofred mud, rice husk ash, and diatomaceous earth as raw materials to produce a geopolymer-based material. These raw materials constitute the ternary blend of the alkali-activated binder in this study. Red mud was used as the primary source of reactive alumina. It is a waste of bauxite industry, which is estimated to be over 2 billion tonnes worldwide (Klauber et al. 2011). Rice husk ash was used as the primary source of reactive silica. Itis a by-product of burning agri-waste particularly rice husk,with an estimated generation rate of over 20 million metric tons per year worldwide (Zemke and Woods 2009; Bronzeoak Ltd 2003; Siddique et al. 2011). It is highly porous, lightweight material with very goodpozzolanicproperties which is used to produce cheap insulating refractory materials (e.g., see Kapur 1980).On the other hand, diatomaceous earth is a natural mineral with an estimated global reserve of around 900 million tonnes (Klein 2006;Indian Minerals Yearbook 2011 (Part

II) 2012). This mineral which is also abundant in some parts of Vietnam contains both silica and alumina and has been used to produce lightweight material with high thermal insulation capacity (Do and Nguyen 2010; Yilmaz and Ediz 2008).

Previous studies have been reported on geopolymers produced from either a mixture of red mud and rice husk ash (Zhang and He 2011) or a mixture of rice husk ash and diatomaceous earth (Pimraksa et al. 2011). However, no studies have been reported on geopolymers produced from a ternary blend of these raw materials.Thisstudy aims to evaluate the engineering properties of lightweight heat-resistant geopolymers produced from a ternary blend of red mud, rice husk ash and diatomaceous earth. This present work is therefore not only intended to understand the impact of mix design on the properties of the said material, but also to aid in the material design through a systematic experimental planning and response surface analysis. The proposed method uses statistical mixture design and multi-objective simultaneous optimization techniqueto find an optimal mix formulation that would meet the desired engineering specification of the geopolymer-based material.

2. Materials and Method

2.1 Raw materials

Red mud (RM) waste was obtained from the Tan Rai Bauxite Plant (Lam Dong, Viet Nam) whereas the diatomaceous earth was obtained fromLam Dong Minerals and Building Materials Joint-Stock Company, Viet Nam.Both RM and DE after being dried for 24 hours were ground in 30 minutes by a ball miller and then sieved using a 90μm-mesh.On the other hand, the rice huskash (RHA) was produced from the burning of rice husk at 650^0C for one hour in the furnace. The rice husk wasobtained from the agricultural waste in Dong Thap province, a local of the Mekong Delta, Vietnam. Theburned rice husks were also ground in 30 minutes and sieved afterwards to produce RHA.

Table 1 summarizes the chemical composition of these alumino-silicate raw materials.As indicated in XRD pattern of these materials (see **Figure 1**), the raw materials contain both amorphous alumina and silica (Nguyen et al. 2013a, 2013b) suitable for geopolymerization reaction at high alkaline condition. Indication suggests also the presence of clay minerals in the diatomaceous earth.As for the alkaline activator, water glass or sodium silicate solution (32% SiO_2, 12.5% Na_2O and 55% H_2O)with a silica modulus of 2.5 was used.

Table 1. Chemical composition (by weight) of RM, RHA, and DE (Nguyen et al 2013a, 2013b)

Raw Material	Al_2O_3	SiO_2	Fe_2O_3	Na_2O	K_2O	CaO	TiO_2	Others	L.O.I	Moisture content (%)
RM	18.98	4.52	49.90	2.60	0.05	0.87	5.62	0.94	16.52	2.66
RHA	1.12	90.90	0.54	-	4.66	1.41	-	0.60	0.77	0.23
DE	16.63	49.61	16.81	0.06	2.01	1.00	1.51	2.73	9.64	7.03

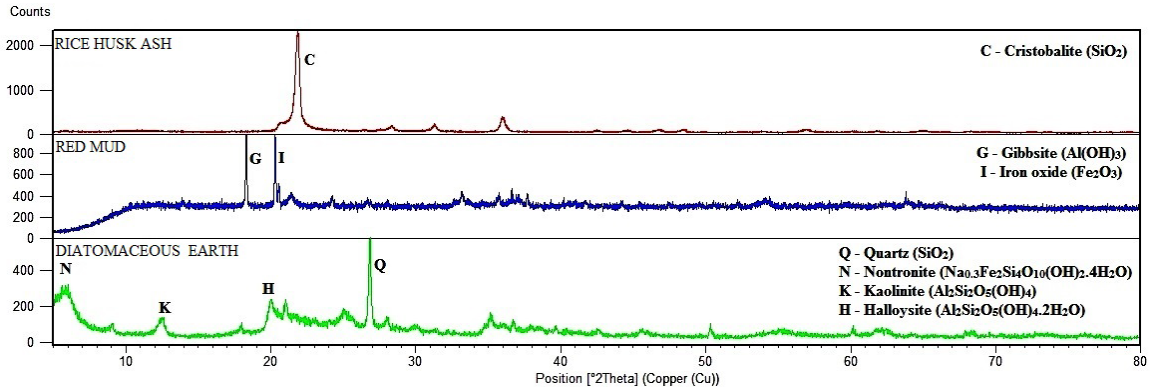

Figure 1. XRD pattern of RHA, RM, and DE (Nguyen et al 2013a, 2013b)

2.2 Mix proportion and mixing

To study the effect of proportioning of the ternary blend of RM, RHA and DE to the engineering properties of the geopolymer product, a statistical mixture design known as the augmented simplex lattice mix design was used (Anderson and Whitcomb 2002;Menezes et al. 2008). **Figure 2** illustrates the 10 mix proportions used in this study with the corresponding points in the ternary diagram of the raw materials.

Specimen	Proportion (%)		
	RM	RHA	DE
A1	100	0	0
A2	0	100	0
A3	0	0	100
A4	50	50	0
A5	50	0	50
A6	0	50	50
A7	66	17	17
A8	17	66	17
A9	17	17	66
A10	33.3	33.3	33.3

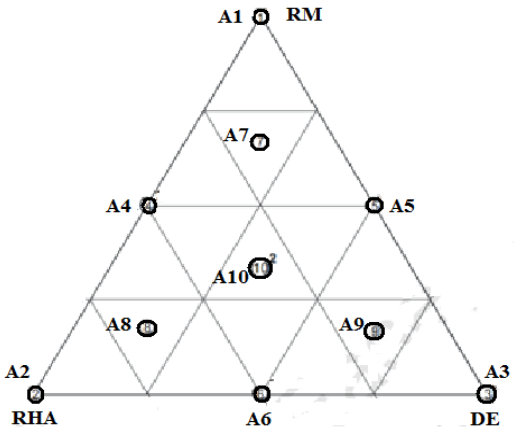

Figure 2. Mix proportions used in the design of experiment

The powdered raw material wasprepared according to the designed proportion and then mixed with 15% (by weight of the powdered solid) water glass solution for 20 minutes using a laboratory cement mixer (Khale and Chaudhary 2007). Water isalso added to adjust the pH value ofthe paste mixture to around 12. The fresh geopolymer paste was molded to a standard cubic size (50 mm x 50 mm x 50 mm) and cured at room temperature condition (30^{o}C, 80% humidity) for 28 days. After curing, these specimens were tested for engineering properties. At least three cured specimens were prepared prior to each test. **Figure 3** depicts the flow of the experimental process. The mixing process and specimen preparationarethen repeated for all mix proportions.

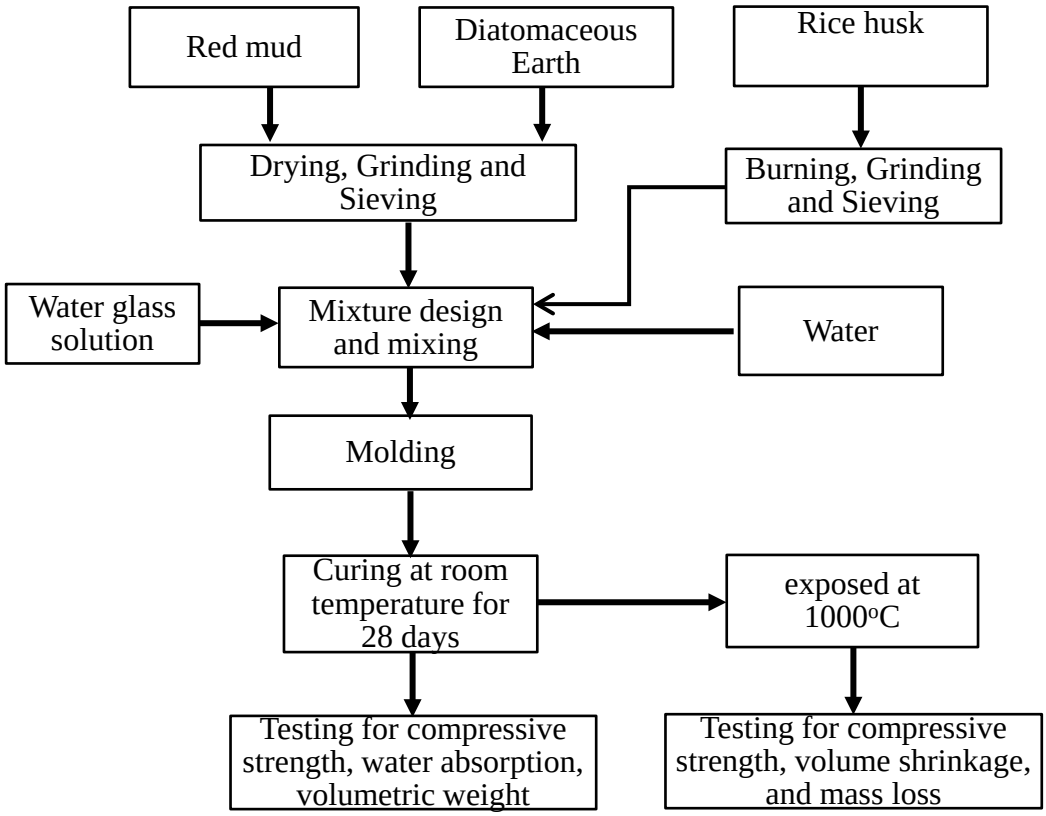

Figure 3. Flowchart of the experimental process

2.3 Experimental testing detail

Compressive strength (MPa)and volumetric weight (kg/m^3) tests were performed for the 50-mm cube specimens according to ASTM C109/C109M. On the other hand, water absorption test specified by ASTM C140 was also performed. Material properties particularly mass loss (%), volumetric shrinkage (%) and change in compressive strength (%) were also determined after subjecting the specimen to elevated temperature. The specimens were exposed at 1000^{o}C for two hours inside a furnace with a heating rate of 5^{o}C/min, and a natural cooling process to reach room temperature (30^{o}C) afterward (Kong et al. 2007; Pan et al. 2012). Mass loss or change in weight refers to the percentage of mass change before (at room temperature) and after exposure at high temperature (1000^{o}C) for 2 hours (ASTM C356-87).Volumetric shrinkage refers to the percentage of volume change before and after exposure at high temperature (1000^{o}C) for 2 hours (ASTM C210). On the other hand, the heat resistance in terms of compressive strength was computed based on the percentage change of 28-day compressive strength before and after exposure at 1000^{o}C for two hours (Kong et al 2007; Pan et al 2012).

2.4 Multiple response surface method and desirability function

Multiple response surface method through the use of desirability function approach is one of the widely used statistical tools to solve multiple response variable problems and optimize one or several responses (Derringer and Suich 1980; Myers and Montgomery 2002; Bayramov et

al.2004; Akcay and Tasdemir 2009). Inresponse surface methodology (RSM),a polynomial function is commonly applied to approximate the form of relationship between the response variable y_i and k independent variables (Khuri and Cornell 1996). This method was initially developed by Box and Wilson in 1951 (as cited by Osborne et al. 1997)to optimize a response variable by determining the most appropriate set of input when the functional relationship among the variables is unknown, but then later extended to multiple response variables. The proposed desirability function approach extends the RSM to m response variables incorporating the experimenter's priorities on the response functions in the optimization process. The response surface for each dependent variable is first established through a regression model. A desirability function is then developed where each y_i is transformed into a desirability value d_i that could range from 0 to one. If the response variable is in an unacceptable range, the desirability value is 0 whereas if the response variable has the optimal value, the desirability value is 1. The overall desirability function D is defined as the weighted geometric mean of the individual desirability values and is calculated as follows:

$$D = (d_1^{r_1} \times d_2^{r_2} \times \ldots d_k^{r_m})^{\frac{1}{\sum_{i=1}^{m} r_i}} \quad (1)$$

where$m$ is number of responses, r_i represents the rating of importance of k^{th} response that varies from the least important (a value of 1), to the most important (a value of 5). This provides an overall assessment of the combined response surface models and flexibility in weighting each of them.Then, the optimal conditions for m responses are obtained by finding the global optimum maximized the overall desirability D.

In this study, the response variable was defined as a polynomial function of three independent variables with 8 terms as described by the following equation:

$$Y_i(x) = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_4x_1x_2 + b_5x_1x_3 + b_6x_2x_3 + b_7x_1x_2x_3 \quad (2)$$

where $0 \le x_i \le 1 \; \forall \; i = 1..3$; $\sum_{i=1}^{k=3} x_i = 1$. The response variable ($Y_i(x)$) refers to the engineering property of geopolymer as a function of mix proportions (x_i) of the ternary blend namely RM (x_1), RHA (x_2), and DE (x_3). The models were evaluated for each response variable by means of regression analysis. The significant terms in the regression model were also found by using the analysis of variance (ANOVA) for each response.Model building based on backward elimination step-wise regression technique was employed and model adequacywas also checked as described in Bayramov et al. (2004) to establish the response surface model. Those terms in the regression model which has p-value greater than the chosen significance level (e.g., α = 0.05) are removed until the resulting model contains only significant terms. Note that the principle of natural hierarchy is first considered such that the presence of higher-order terms requires the inclusion of all lower-order terms contained within those of higher order.Response surface analysis including desirability function approach was implemented through the Design-Expert 8.0.7 software (Stat-Ease Inc., Minneapolis, MN).

In the case of compressive strength and heat resistance wherein the response variables are to be maximized (larger-the-better type), the individual desirability function is defined as follows:

$$d_i(Y_i) = \begin{cases} 0 & Y_i < L_i \\ \left(\dfrac{Y_i - L_i}{T_i - L_i}\right) & L_i \le Y_i \le T_i \\ 1 & Y_i > T_i \end{cases} \quad (3)$$

In the case of water absorption, volumetric weight, mass loss, volumetric shrinkage wherein response variablesare to be minimized (Smaller-the-better type), the individual desirability function is defined as follows:

$$d_i(Y_i) = \begin{cases} 0 & Y_i > U_i \\ \left(\dfrac{U_i - Y_i}{U_i - T_i}\right) & T_i \le Y_i \le U_i \\ 1 & Y_i < T_i \end{cases} \quad (4)$$

where$\boldsymbol{L_i}$ and $\boldsymbol{U_i}$ represent the acceptable lower and upper limits respectively, and $\boldsymbol{T_i}$ represents the target value of the $\boldsymbol{i^{th}}$ response. Note that if any one of the responses cannot meet engineering specification requirement, the desirability $\boldsymbol{d_i}$ is equal to zero, and consequently the overall desirability $\boldsymbol{D}$ is also zero.

3. Results and Discussion

3.1 Engineering properties of geopolymer product

Table 2 summarizes the results of the experimental test done on the 10 specimens. All geopolymer specimens after 28 days were having low volumetric weight. These values range from 1100 to 1660 kg/m^3. Specimens A2, A3, A6, A8, A9, and A10 are less than 1300kg/m^3 which is less than the prescribed volumetric weight (1680 kg/m^3) for a lightweight concrete brick (ASTM C55-99 ASTM C90-99a).

As for water absorption, the A8 specimen has the lowest value(165 kg/m^3)whereas A9 has the highest value(387 kg/m^3). Nevertheless, the water absorption values of the geopolymer were still lower than 288 kg/m^3 which is the prescribed limit according to ASTM C55 or C90 requirements for lightweight concrete brick material.

The 28-daycompressive strength of the specimens ranges from 4 to 15 MPa. Specimens A8 and A10 were above 11.7 MPa, which is the prescribed strength for concrete brick according to ASTM C55 and C90-99a standards.

As for heat resistance in terms of percentage change in compressive strength, most of the geopolymer specimen demonstrated strength gain except for that of A1 (100% RM) and A3 (100 % DE). The specimens A1 and A3 exhibited cracks after exposing them at 1000^{o}C for 2 hours. A8 (17%RM-67%RHA-17%DE) specimen exhibited the largest percentage of strength gain (165%) at elevated temperature because of the sintering effect analogous to ceramics (Schomburg, 2000; Sglavo et al, 2000).

Another parameter for thermal stability of the material are its mass loss and volumetric shrinkage when exposed to high temperature. As shown in **Table 2**, mass loss of geopolymer specimens after exposure at 1000^{o}C are less than 20.5%. Geopolymer specimens containing high percentage

of RHA have values of lower mass loss that is around 6 to 8% (specimens A2-100%RHA, A6-50%RHA, and A8-67% RHA) compared to other specimens which contain higher DE or RM. This could be explainedby the presence of clay minerals as well as organic impurities in both DE and RM, which could easilydecomposed into water vapor and CO_2 when exposed at high temperature (Sglavo et al. 2000 and Yilmaz and Ediz 2008). This is also reason why these samples have higher volumetric shrinkage than the other specimens. For example, the best specimens are A2, A6, and A8 in terms of volumetric shrinkage with values of 0.84%, 5.70%, and 5.38%, respectively. Note that the prescribed limit of mass loss and volumetric shrinkage should be less than 10.7 % and 10.0 %, respectively(ASTMC210-95 and C356-87).

Table 2. Engineering properties of geopolymer specimen

Samples	Volumetric weight (kg/m^3)	Water absorption (kg/m^3)	28-day Compressive strength (MPa)		Volumetric Shrinkage (%) at 1000^oC	Mass loss (%) at 1000^OC
			30^oC	1000^oC		
A1	1656±15	361.66±3.60	6.21±0.02	0[a] (-100 %)[b]	7.38±0.05	20.51±0.25
A2	1104±10	315.09±3.25	12.03±0.14	16.20±0.18 (34.66 %)[b]	0.84±0.01	6.77±0.02
A3	1301±12	386.65±4.00	7.02±0.03	0[a] (-100 %)[b]	23.18±0.25	18.77±0.20
A4	1473±14	229.16±2.35	10.01±0.12	18.25±0.20 (82.32 %)[b]	9.79±0.05	13.17±0.15
A5	1572±15	358.13±3.70	6.12±0.02	16.22±0.18 (165.03 %)[b]	29.27±0.30	18.75±0.20
A6	1316±12	241.25±2.50	11.64±0.12	13.21±0.15 (13.49 %)[b]	5.07±0.02	8.76±0.03
A7	1608±15	248.04±2.55	8.22±0.05	18.22±0.20 (121.65 %)[b]	17.44±0.18	15.04±0.16
A8	1288±12	165.14±1.85	14.30±0.15	20.06±0.25 (40.28 %)[b]	5.38±0.03	8.23±0.03
A9	1293±12	320.78±3.25	9.02±0.08	14.40±0.16 (59.64 %)[b]	19.02±0.25	16.21±0.18
A10	1317±12	193.39±2.00	12.65±0.14	17.34±0.20 (37.08 %)[b]	18.15±0.25	13.09±0.15

Note: [a] Crack formed in the specimen.
[b] heat resistance in terms of percentage change in compressive strength (%)

3.2 Optimization based on multi-response surface analysis

Experimental data from the mixture design were fitted with response surface models wherein properties are functions of mix proportions of RM, RHA and DE as shown in the following equations:

Volumetric weight (kg/m^3) = 1710.80*RM+1150.80*RHA+1316.80*DE (5)

Water absorption (kg/m^3) = 347.76*RM + 309.07*RHA + 389.22*DE
– 561.84 *RM*RHA – 530.53*RHA*DE (6)

Compressive Strength (MPa) = 5.78*RM + 13.52*RHA + 7.13*DE
+ 98.76*RM*RHA*DE (7)

Heat resistance
in terms of strength gain (%) =70.53*RHA–48.66*RM–92.27*DE+963.49*RM*DE (8)

Volumetric Shrinkage (%) = 7.53*RM + 0.49*RHA + 22.75*DE
+24.17 * RM * RHA
+57.24* RM * DE
-27.47 * RHA * DE (9)

Mass loss (%) = 19.39*RM+6.37*RHA+18.89*DE-15.62*RHA*DE (10)

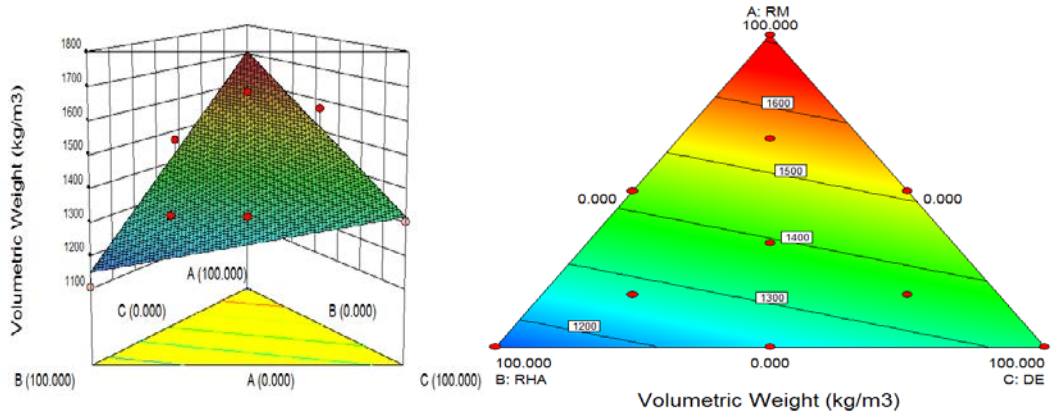

Figure 4.Response surface plots of volumetric weight of geopolymer specimens and their projections onto the ternary diagram.

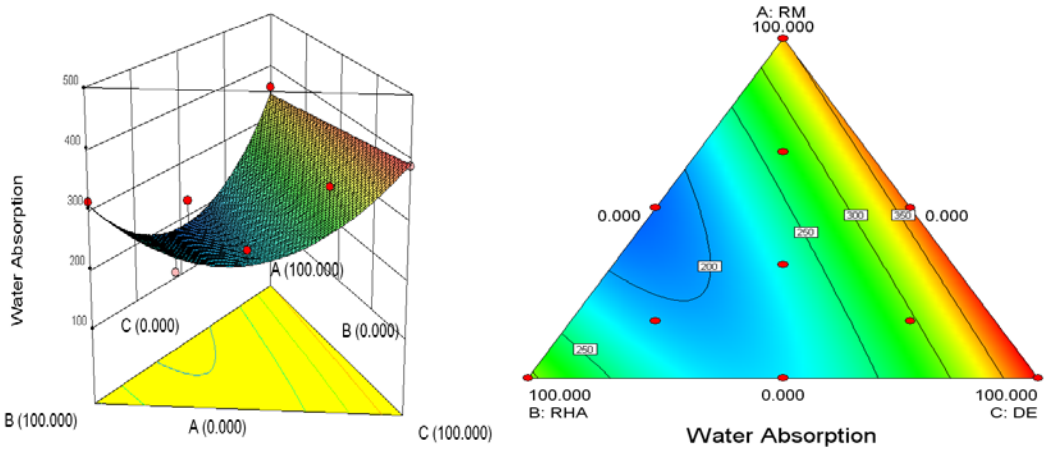

Figure 5.Response surface plots of water absorption of geopolymer specimens and their projections onto the ternary diagram.

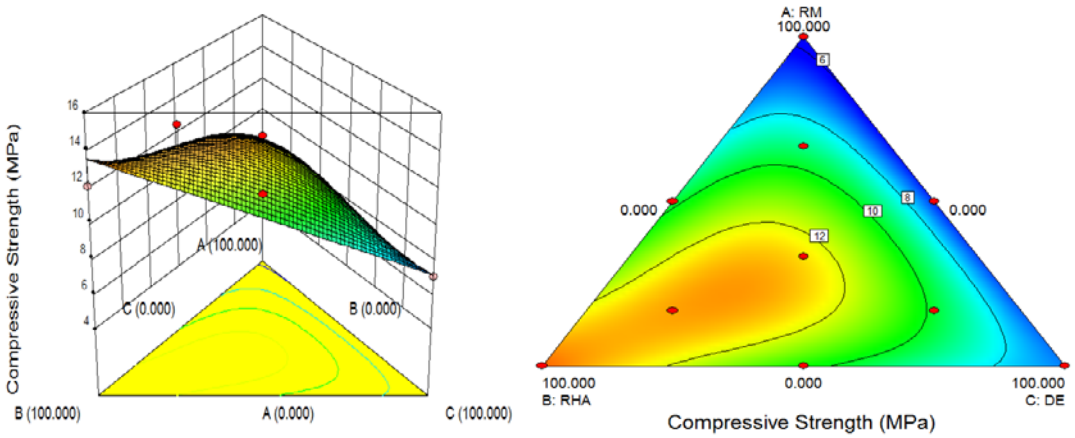

Figure 6.Response surface plots of 28-day compressive strength of geopolymer specimens and their projections onto the ternary diagram.

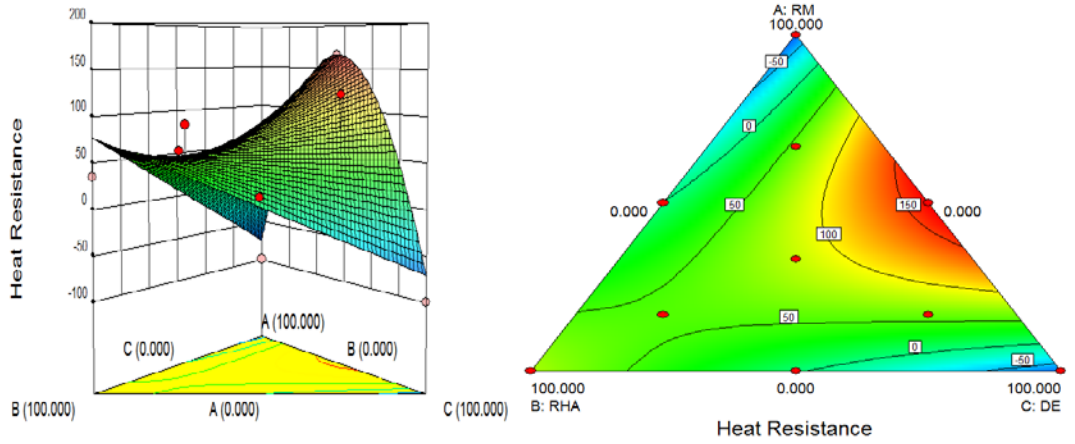

Figure 7.Response surface plots of heat resistance in percentage change of compressive strength of geopolymer specimens and their projections onto the ternary diagram.

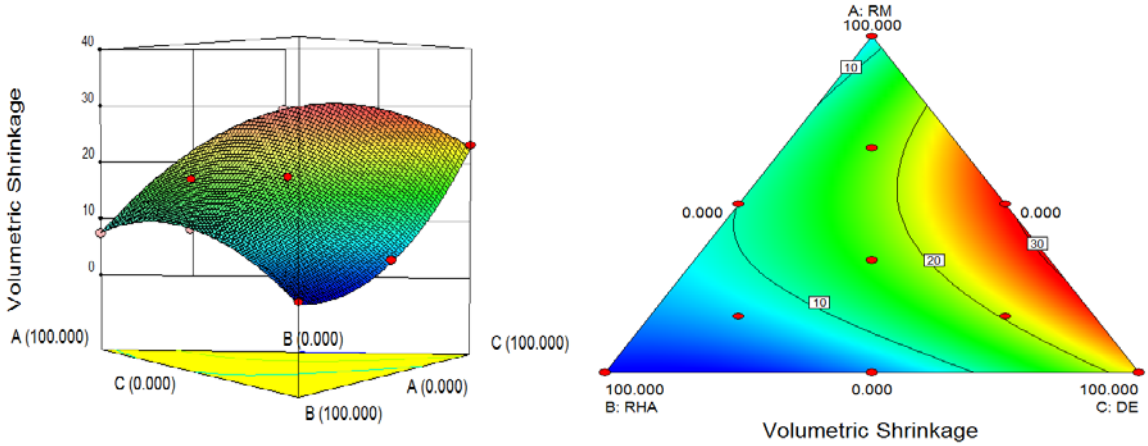

Figure 8.Response surface plots of volumetric shrinkage of geopolymer specimens and their projections onto the ternary diagram.

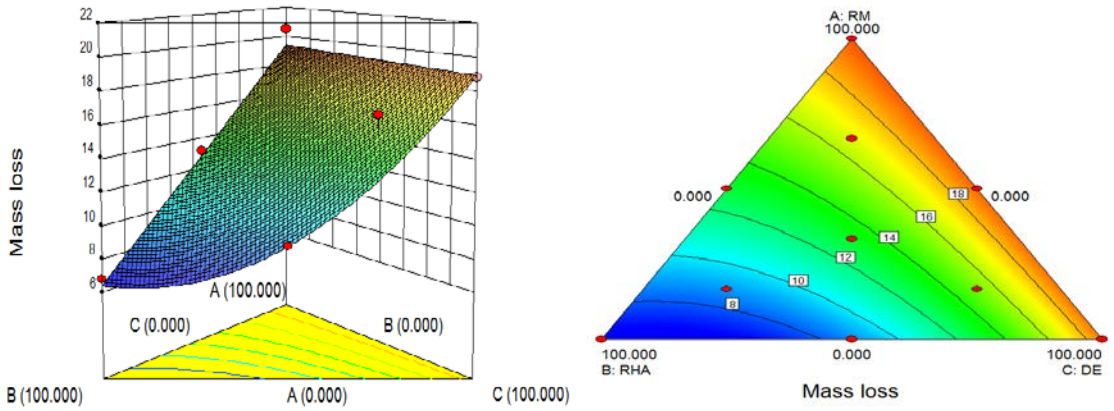

Figure 9.Response surface plots of mass loss of geopolymer specimens and their projections onto the ternary diagram.

Figures 4-9show the projection of response surfaces onto the ternary diagram as contour plots of the property. Indication from these response surface models suggests that a high proportion of rice husk ash (RHA) relative to red mud (RM) and diatomaceous earth produce a lighter but stronger and more thermally stable geopolymer. The models also suggest the significant interaction effect among the raw materials on the properties of the geopolymer particularly the compressive strength, water absorption, volumetric shrinkage, and mass loss. The high silica in RHA and DE reacted to the alumina in RM and DE at high alkaline condition (pH around 12) to form a three-dimensional geopolymer network resulting to a stronger and heat resistant binder (Davidovits 2011). However, a high proportion of RHA could also result an undesirable increase of water absorption property of the material. As indicated in the response surface model, the amount of RHA in the formulations could thus be increased without causing an increase of water absorption by using an appropriate combination of RM and DE in the mixture. On the other hand, therelatively large proportion of DE and RM in the mix could affect the thermal stability of the product due to their high LOI and the presence of clay minerals in the raw material (Sglavo et al. 2000; Yilmaz and Ediz 2008). It is therefore imperative to find an optimal formulation of these raw materials to produce a material with desired specifications.

The desirability function approach was then used to determine the optimum proportions of RM, RHA and DE to produce a light-weight heat-resistant geopolymer by simultaneously maximizing the 28-day compressive strength and heat resistance in terms of change in compressive strength, and minimizing the volumetric weight, water absorption, mass loss and volumetric shrinkage. Table 3 summarizes the optimization parameters used including the constraints based on the desired specifications.For the weighting of the individual desirability, the compressive strength and water absorption were considered the most important engineering properties in the product design and were given an importance rating of 5, followed by volumetric weight and heat resistance with a rating of 3, and the mass loss and volumetric shrinkage were given an importance rating of 1. Results of the multi-response surface optimization by maximizing the overall desirability are shown graphically in **Figure 10.**The green-shaded region in the ternary

diagram of this figure indicates possible mix formulations that would meet the desired engineering specifications of the material.

Table 3. Definition of optimization parameters including constraints in the multi-response optimization problem

Name of factors and responses	Goal	Lower limit	Upper limit
A: RM	Is in range	0	100
B: RHA	Is in range	0	100
C: DE	Is in range	0	100
Compressive Strength (MPa)	Maximize	11.7	14.3
Water Absorption (kg/m^3)	Minimize	165.14	288
Volumetric Weight (kg/m^3)	Minimize	1104	1680
Heat Resistance (%)	Maximize	0	165.03
Mass loss (%)	Minimize	6.77	10.7
Volumetric shrinkage (%)	Minimize	0.84	10

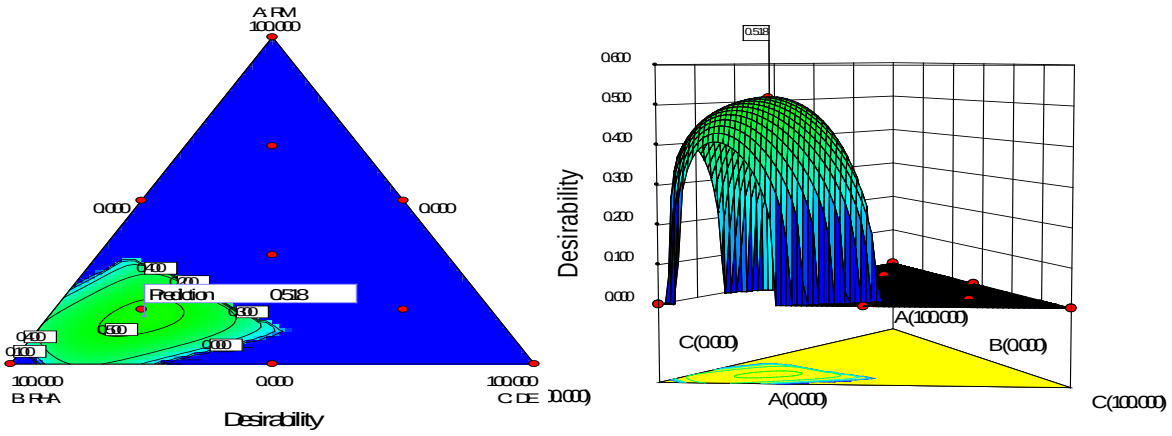

Figure 10. Response surface and contour plot of the overall desirability for the multi-response optimization problem.

The maximum overall desirability D of 0.518was achieved at the following mix proportion: 14.49% RM, 67.17% RHA and 18.34% DE. At this optimal mix of the ternary blend, a geopolymer is produced with the predicted engineering properties of a lightweight heat-resistant material as shown in **Table 4.** The predicted values from the model using the optimal mix proportion were also verified by an additional experimental study. The test results are also shown in **Table 4**.The results indicate thatthe properties of geopolymer specimens produced from the confirmatory tests were in good agreementwith the predicted values of the response surface models, and also meet the desired engineering specification set for the material.

Table 4. The properties of geopolymer based from the predicted values of response surface models and experimental values of confirmatory tests using the optimal mix.

	Predicted values	Experimental values	Desired Specification
Compressive Strength (MPa)	12.99± 1.26	13.25 ± 0.50	> 11.7
Water Absorption (kg/m^3)	209.34± 41.41	210.93 ± 5.75	< 288
Volumetric Weight (kg/m^3)	1262.38± 72.58	1270 ± 25.18	< 1680
Heat resistance (%)	49.01± 54.45	56.75 ± 4.25	> 0
Mass loss (%)	8.63± 1.12	8.30 ± 0.05	< 10.7
Volumetric shrinkage (%)	6.08± 1.57	6.24 ± 0.03	< 10

4. Conclusion

This paper presents an experimental study to produce and optimizea light-weight heat resistant geopolymer-based material from a ternary blend of red mud waste, rice husk ash and diatomaceous earth. The proposed optimization process involves the following steps: 1) performing statistically designedexperiments based on mixture design; 2) developing the response surface models to predictthe engineering properties of the geopolymer; 3) determining the optimal mix of such ternary blend that will maximize the overall desirability function of the engineering properties given the specification requirement as constraints; and 4) performing confirmatory runs using the optimal mix to verify the mathematical model. In this study, the powdered aluminosilicates with an optimal mix of14.49% RM, 67.17% RHA and 18.34% DE, and alkaline-activated with 15% (by weight of solids) of water glass (silica modulus of 2.5) producedgeopolymers with an average 28-day compressive strength of 13 MPa, water absorption of 210 kg/m^3, volumetric weight of 1270 kg/m^3, and a mass loss, volumetric shrinkage, strength gain of 8%, 6%, 57% when exposed at 1000^{o}C, respectively. These values were in good agreement with the predicted values of the developed model; thus, demonstrating the adequacy of the method in mix proportioning for a desired geopolymer product. The ternary-blended geopolymer can thus be potentially used as lightweight heat-resistant material for masonry walls or partitions.Future studies will consider chemical resistance of the material and other thermal properties such as thermal conductivities, thermal expansion coefficient, among others in the design and evaluation of the ternary-blended geopolymerbinder. Microstructure of these geopolymerswill also be studied further to understand the relationship among composition, microstructure and macroscopic properties of such materials.

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