Optimum mix design of high-performance concrete containing micro POFA using historical data design

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Abstract. This paper presents the optimized mix design based on the response surface methodology (RSM) in producing high performance concrete (HPC) by utilizing palm oil fuel ash (POFA) as cement replacement material. The historical data design was used based on the existing testing data determined from the laboratory experiments. The variable in this study includes POFA percentage (10%, 20%, and 30%). The concrete mixes were tested both for fresh and hardened properties of high performance concrete. The optimized level for POFA in the HPC mix proportion was determined by the maximization of workability, early, 28 days’, and later compressive strength. The response of each mix that contains POFA showed a significant increase in the workability and compressive strength with respect to the plain HPC. The results presented the optimum solution for mix design of high performance concrete with POFA that achieve the targeted goal performance criteria (fresh and hardened properties).

1. Introduction
Global demand of cement in construction industry is expected to increase to 400% by year 2050 [1]. Based on the human activity category, 5-8% of current global CO₂ was contributed from cement production [2]. Due to that, the urgency of finding the alternative way to reduce the impact on the earth resources was raised by the International Energy Agency (IEA). One of the alternative options that considered realistic is using the ‘blended cement’ which replacing cement with other waste material that contains cementitious properties. These materials are called supplementary cementitious materials (SCM). SCM such as rice husk ash, fly ash, ground granulated blast slag and metakaolin have been utilised to lower the impact on the environment [3-6]. Furthermore, the incorporation of the SCM in concrete has been reported to improve the mechanical properties of concrete [7-10].

Malaysia as one of the biggest players in palm oil industry in the world is now facing the difficulties in handling the waste product from the palm oil mills. This is due to the fact that the material is dumped near the mill and thus creating negative effect on the natural environment [11]. The palm oil biomass amount is expected to increase of up to 100 million dry tons in the year of 2020 [12]. Generally, 5% of the palm oil fuel ash (POFA) is produced after the burning process in the boiler [13]. POFA is generated from the burning process of palm fruit residues for generation of electricity. The process of burning in the furnace will convey the palm fruit fibres to the chimney in the form of fly fuel-ash. [14]. Research on POFA has been started in 1990 and found to be a good pozzolanic material and has the potential to improves the engineering properties of concrete and durability performance as well [15-16].
Knowing the fact that POFA can enhance the mechanical properties and its environmental impact, it is deemed necessary to develop the high-performance concrete mix containing POFA as the SCM. A statistical experimental design procedure called response surface methodology (RSM) was used for modeling and analyzing of problems in which response or output variables are related to the number of input variables [17]. This study aimed to apply the RSM to relate POFA dosage to the fresh and hardened properties of high-performance concrete in order to obtain the optimum mix design. For the fresh properties, the slump value as the indicator of the workability of the concrete and the compressive strength as the main property of high-performance concrete in optimization process.

2. Materials and method

The cement used is Type I Portland Cement from the company Cahya Mata Sarawak. The specific gravity of cement is 3.15. POFA used in this study was collected from Bekenu, Sarawak. The total content of silica, aluminium and ferum oxide is 69.7%. From this information, it shows that POFA having higher percentage of silica content that can contribute to the strength of concrete. Based on ASTM C618-15[18], micro POFA (45µm) used in this study can be classified as Class C due to the total content of silica, aluminium and iron oxide below 70%. Crushed granite from a local source with size ranges from 9.5 mm to 20 mm was used. The grading of the aggregates was according to ASTM C 33-16[19] with the aggregate crushing value (ACV) of 22.5%. The fineness modulus, specific gravity and water absorption of the coarse aggregates used are 2.2, 2.69 and 0.5% respectively. The fineness modulus was 0.99. Therefore, in this study, the combination of river sand and quarry dust with weight ratio of 1:1 was used as fine aggregates. The superplasticizer that was used is Real Set231SD which was formulated from a selected highly purified lignosulphonate and it does not contain calcium chloride.

2.1. Mix proportion

The mix design for high performance concrete was designed based on ACI 211-4R[20] guidelines. From the guidelines, the mix proportion of high performance concrete is presented in Table 1.

| Component       | Weight |
|-----------------|--------|
| Cement          | 620 kg/m³ |
| Coarse Aggregates | 1105 kg/m³ |
| Fine Aggregates  | 556 kg/m³  |
| Water with superplasticizer | 180 kg/m³ |

2.2. Design of experiment using RSM

Response surface methodology (RSM) using Design Expert Software (DES) was applied in this study to obtain the optimum mix design of high performance concrete containing POFA. Under the RSM, the Historical Data Design (HDD) was used to evaluate the previous obtained experimental data. Table 2 shows the actual and coded values with the variables. The POFA dosage was chosen as the input variable and four predicted responses (slump, early strength, 28-day strength and later strength) were targeted. The relationship can be approximated by the second order polynomial.

| Variables | Code | Unit | Coded parameter value |
|-----------|------|------|-----------------------|
| POFA      | X₁   | %    | -1 0 1                |

Table 1. Mix proportion of high-performance concrete.

Table 2. Variable and the actual and coded values.
2.3. Slump test
ASTM C143-15 [21] was followed to perform the slump test of concrete. Three layers of equal volume were filled and each layer was tamped with rod 600 mm long and 16 mm diameter.

2.4. Compressive strength test
ASTM C109-16[22] was followed to determine the compressive strength of concrete at the early age of 7, 28, 56 days. 45 cubes specimens of 100 x 100 x 100 mm in dimensions were prepared with different percentage POFA as shown in Table 2.

3. Results and discussion
Table 3 shows the run of experiments with the variable and the actual/measured response.

Table 3. Experimental variable and responses.

| Exp. run | Variable in coded levels | R1 (mm) | R2 (MPa) | R3 (MPa) | R4 (MPa) |
|----------|--------------------------|---------|----------|----------|----------|
| 1        | 0                        | 85      | 56.5     | 58.5     | 58.5     |
| 2        | 1                        | 75      | 56.5     | 58.5     | 56.5     |
| 3        | 0                        | 80      | 59.5     | 58.5     | 56.5     |
| 4        | -1                       | 90      | 65       | 65       | 65       |
| 5        | -1                       | 95      | 65       | 65       | 65       |
| 6        | -1                       | 92      | 66       | 55       | 66       |
| 7        | 1                        | 78      | 55       | 57.5     | 55       |
| 8        | 1                        | 75      | 57.5     | 56       | 57.5     |
| 9        | 1                        | 75      | 56       | 56.5     | 56       |
| 10       | -1                       | 90      | 65       | 66       | 65       |
| 11       | 0                        | 85      | 58.5     | 65       | 59.5     |
| 12       | 0                        | 80      | 58       | 59.5     | 58       |

Based on the statistical analysis using Design Expert Software, each of response can be predicted by the following regression equation:

\[
Y_{R1} = 83.33 - 8X 
\]

\[
Y_{R2} = 58.13 - 4.5X + 2.62X^2 
\]

\[
Y_{R3} = 58.88 - 4.31X + 2.06X^2 
\]

\[
Y_{R4} = 58.13 - 4.5X + 2.62X^2 
\]

where \(Y\) is the predicted response, the suffix R1, R2, R3 and R4 represents the slump, early compressive strength, 28-day compressive strength and later compressive strength, respectively. The equations above can be used to determine the predicted slump, early compressive strength, 28-day compressive strength and later strength of high performance concrete containing POFA. In this analysis, several models were compared and the aliased model was ignored. The best model indicates the low standard deviation (Std. dev) and high R squared (\(R^2\)) statistics due to the models fitted well with the experimental data [23]. Amongst the models, only slump was suggested a linear model while the early, 28-day and later compressive strength were found to be significant. Table 4 shows the full analyses of the regression
models. The value of the R squared provides a correlation between the measured and predicted response. The adjusted R squared (adj. R$^2$) also provides the same correlation but without the insignificant term considered [24]. It can be observed from this table that the adj. R$^2$ for all the responses are in good agreement with the predicted R squared (pre. R$^2$).

| Response | Std. dev | R$^2$ | Adj. R$^2$ | Pre. R$^2$ |
|----------|----------|-------|------------|------------|
| R1       | 2.29     | 0.9067 | 0.8974     | 0.8711     |
| R2       | 0.98     | 0.954  | 0.9438     | 0.9183     |
| R3       | 0.54     | 0.98   | 0.9803     | 0.9713     |
| R4       | 0.98     | 0.954  | 0.9438     | 0.9183     |

Result of analysis of variance show that the variable in the high performance concrete mix has significant effects on the four target responses. The accuracy of the model selection was validated by the lack-of-fit test. The significant lack-of-fit provides a values of “Prob. > F” less than 0.05 which indicates the test at the 95% confidence level. Analysis of variance (ANOVA) for each of the response and all the sources are showed significant result due to the Prob. > F values are less than 0.05.

A numerical optimization was done to determine the optimum mix design of high-performance concrete containing POFA. The desired goal for each of the responses were set in the software in order to achieve desirable mix design. Table 5 shows the optimization criteria used in this study.

| Response                              | Limits  | Importance | Goal       |
|---------------------------------------|---------|------------|------------|
|                                       | Upper   | Lower      |            |
| Slump                                 | 90      | 95         | In range   |
| Early compressive strength            | 50      | 55         | 3          | Maximize   |
| 28-day compressive strength           | 60      | 65         | 3          | Maximize   |
| Later compressive strength            | 60      | 65         | 3          | Maximize   |

The optimization result based on numerical was used to satisfy the criteria for each of the response. The optimum solution obtained from the analysis is presented in Table 6. The desirability of the optimum solution is 0.915. The maximum micro POFA percentage replacement is 10% with all targeted responses were achieved. Similar finding also reported that 10% of micro POFA yielded the highest compressive strength of high performance concrete. However, current finding also showed that higher compressive strength of concrete can be achieved by enhancement of nano POFA in the mix design [25].

| Variable and response                |
|-------------------------------------|
| Cement                              | 558 kg/m$^3$ |
| POFA                                | 62 kg/m$^3$  |
| Slump                               | 91 mm        |
| Early compressive strength          | 60 MPa       |
| 28-day compressive strength         | 65 MPa       |
| Later compressive strength          | 65 MPa       |
| Desirability                        | 0.915        |
4. Conclusions
From this study, the measured data were obtained from the experimental program and were analysed using response surface methodology (RSM) to obtain the valid regression model for each response. The compressive strength response showed the quadratic function except the slump behaved more as a linear function. The value of $R^2$ for each response showed a high value which correspond to the well fitted of models with the measured data. Furthermore, the adjusted and predicted $R^2$ values were also in a good agreement. Along with that, the analysis of variance showed that all the models have significant effect on the targeted responses. With the results of the good model, a numerical optimization was carried out and one optimal solution was obtained for the mix design of high performance concrete containing POFA. The optimum mix satisfies and improves the slump and compressive strength of the concrete with the utilizing 10% POFA as supplementary cementitious material.

5. References
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