

Optimization of EMI shielding effectiveness plaster mortar containing POFA using Taguchi design and Flower Pollination algorithm method

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Abstract: A waste material which is collected from palm oil mill called POFA is used as cement replacement in plastering work to overcome electromagnetic interference issue. In the experiment, variables involved POFA admixture percentage (weight %), topcoat powder-to-binder ratio, water-to-binder ratio, latex agent content (weight%), particle size of POFA (μm) and curing conditions. The EMI shielding effectiveness (SE) is mainly dependent on all variables, especially POFA admixture percentage and particle size of POFA. A hybrid Taguchi design and flower pollination algorithm (FPA) method was used to optimize the best approaching high EMI SE based on experimental data. The experimental results found that plaster mortar can shield -23dB of electromagnetic wave (EMW) while using FPA method was shielded -24.68dB. The interaction model of EMI SE was derived from regression analysis and the truth found that the EMI SE is dependent on the water-to-binder ratio followed by latex agent content, particle size of POFA and curing conditions. From the FPA process, targeted EMI SE were suggested 30.012% of POFA admixture percentage, 0.3 of topcoat powder-to-binder ratio, 1.03 of water-to-binder ratio, 10% of latex agent content, 45 μm particle size of POFA and air curing condition were optimal variables.

Keywords: EMI shielding; Palm Oil Fuel Ash; Plaster mortar; Taguchi Design; Flower Pollination Algorithm

1. Introduction

In recent times, most of the advance technologies in electrical and electronic devices, especially the wireless and communication systems are polluted by electromagnetic wave (EMW) radiation, which can be harmful to health and may cause of death [1–3]. In order to deal with EMW radiation issue, POFA was used as cement replacement for mitigate the EMW in plastering work. Cement-based composite electromagnetic (EM) absorbing materials, with the advantage of rich resources, with good environmental adaptability and low cost, have being one of the famed research focuses [4–7]. The conventional plaster cement-based composite is containing three main components; Ordinary Portland cement (OPC), sand and water. Usually, the mortar for plastering work was prepared with 1:3 fixed binder-to-sand ratio [8].

The current study stated that EMI shielding in building have been shielded by carbon filling cement materials and metal filling cement composite [9]. The

carbon filling materials consist of graphite, carbon black, coke and carbon fiber. These carbon materials have comparatively high conductivity and EMI shielding [10]. The metal based fillers consist of metal powder, metal fiber and metal alloys, which are used in cement matrix composites [9]. The metals such as silver, copper, and nickel was used for long time as conductive components in polymer due to their high conductivity [9].

Nowadays, Malaysia is one of the largest palm oil industry in the world. Furthermore, as the second largest global palm oil producer, Malaysia has the highest daily wastage [11] from burning of empty fruit bunch, fibre and palm oil shell in the boiler as fuel. This wastage was called as POFA and classified as Class-F fly ash as per ASTM C618 [12]. Currently, POFA usage is very limited and uncontrollable, and most of it is disposed of towards landfills. Consequently, it has caused numerous environmental harms [13, 14]. Earlier, POFA was applied for variety of application and typically used in concrete application. In concrete, POFA was used as filler to increase the strength of concrete [15, 16]. Besides, POFA

was used as pozzolanic material which can improve the durability of the concrete [17].

There are also many other high conductive fillers like silver, copper, and nickel can be use. However, these metal fillers are not only high in cost but very complicated in processing so they are not commonly used in cement matrix composite [9], therefore the POFA was choose to use as filler to mitigate against the EMI. The motivation of using POFA in EMI shielding is to reduce the agricultural waste that is uncontrollably dumped in landfills. Besides that, POFA is containing high carbon and iron III oxide which can be used to prevent the EMW radiation.

There is various type of design-of-experiment (DOE) was applied to optimize the optimal parameter of cement-based application. The Taguchi DOE is one of the familiar method was applied in cement-based application especially in designing the high strength concrete [18–23]. The Taguchi DOE functional need fixed other processing parameters like mineral admixture, water-to-binder ratio, water content, plasticizer content, curing regime and curing condition [18–24]. Taguchi DOE was used for evaluating more influencing factors with fewer experiments [25]. Besides, the Taguchi DOE also was compared with other DOE or statistical tools for validation purpose [26].

To design the new parameter for plaster cement-based composite for EMI shielding-effectiveness, a mix level L_{16} orthogonal array table with six different parameter Taguchi DOE was used. The parameter involved are POFA admixture percentage, topcoat to binder ratio, water-to-binder ratio, latex agent ratio, POFA particle size and curing condition. These parameters involved four and two level respectively. Therefore, mix level L_{16} orthogonal array table with six different parameter Taguchi DOE was selected for this study. Taguchi design usually involve signal to noise ratio (S/N) analysis. The S/N ratio limited to recognize the optimum parameter directly from the list of variable in Taguchi design table. So, the researchers tried a lot of alternatives to develop the result precisely such as cuckoo search algorithm, FPA, swarm algorithm, genetic algorithm, moth search algorithm and others. FPA is proposed to this paper to solve the problem of optimal EMI shielding-effectiveness (SE) parameter. It has only one key parameter p (switch probability) which makes the algorithm easier to implement and faster to reach optimal solution. FPA originally created by Yang [3, 16, 27]. Nowadays, FPA is well-known for researchers to optimize several application problems.

This paper presents the data obtained from a study into the use of POFA in plastering cement-based composite. The data presented include EMI shielding-effectiveness which is design by Taguchi DOE and applied FPA to determine the optimal variable of parameter to accomplish the desired EMI shielding-effectiveness. The application for this research is mainly focus in plastering wall of building which is the wall can absorb the EMW radiation to least the EMI problem.

2. Experimental methods

2.1 Materials

Five main materials were prepared including ordinary Portland cement (OPC), a local river sand, latex agent for plaster cement (LA), topcoat powder (TP) and POFA. The OPC and sand were supplied by Advance Engineering Material Laboratory from University Tun Hussein Onn Malaysia, Johor, Malaysia. TP and LA was supplied by Nas Sutera Engineering Sdn. Bhd. OPC and TP were coming with powder form from supplier. Meanwhile, POFA was supplied from Genting Ayer Hitam Oil Mill, Johor, Malaysia. The fresh POFA was originally supplied in large particles and impurities. POFA was refined by using water-immersion method [28] to wash up the dust. The POFA was dried in oven for 24 hours at $100 \pm ^\circ\text{C}$ and grinded became fine powder. POFA was sieve by $160 \mu\text{m}$ and $45 \mu\text{m}$ sieves to create the fine POFA (FPOFA) and ultra-fine POFA (UPOFA) respectively. Based on the XRF results, the total of silicon dioxide (SiO_2) + aluminium oxide (Al_2O_3) + Iron(III) oxide (Fe_2O_3) of this POFA is greater than 70% with satisfies the chemical composition required for Class-F fly ash as accomplish to ASTM C618 [12]. The chemical composition of OPC, TP and POFA are given in Table 1. The local river sand was used with the grading given in Table 2. This gradation of sand is accordance with the requirement in ASTM C144[29].

Table 1 Chemical composition of OPC, TP and POFA

Composition	OPC (%)	TP (%)	POFA (%)
CaO	59.20	86.50	5.72
SiO ₂	13.60	3.58	62.33
Al ₂ O ₃	3.17	0.99	5.07
Fe ₂ O ₃	2.81	1.19	5.67
MgO	1.35	1.15	1.92
SO ₃	4.09	1.64	0.50
K ₂ O	0.28	0.29	7.55
LOI	15.50	4.68	11.25

Note: Calcium oxide (CaO), silicon dioxide (SiO₂), aluminium oxide (Al₂O₃), iron(III) oxide (Fe₂O₃), magnesium oxide (MgO), sulfur trioxide, (SO₃), potassium oxide (K₂O) and Lost of ignition (LOI)

Table 2 Gradation of sand

Sieve size	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200
ASTM							
Passing (%)	100	100	100	80	35	20	10

2.2 Plastering mortar compositions

All samples were prepared accordance to previous study [8], which is especially for plastering work. The plaster mortar was prepared with 1:3 fixed binder (OPC+POFA)-to-sand ratio according to the P. Chindaprasirt [8] plastering work. All samples were prepared based on mix level L_{16} orthogonal array table of Taguchi design as Table 3 and Table 4 show. All samples were left for 28 days for curing. Based on ASTM C91[30] and real construction industry practice, the mortar was takes 28 days to cure and reach 100% of its strength. FPOFA (160 μm) and UPOFA (45 μm) were used to determine the contribution of particle size in EMI SE. LA for plaster mortar was used to mixed for mortar strengthening. The recommend dosage of this agent is provided by supplier, it is 0 to 10% by weight of cement. TP was containing mainly limestone powder for used as additives to enhance workability, water retention and adhesion as per provided in the usage catalogue technical data sheet. The TP-to-binder ratio is between 0 to 0.3 by weight of binder as per provided in usage manual. The water-to-binder (W/B) ratio was applied based on the previous study[8], it is between 0.6 to 1.2 by weight of binder. Finally, all samples were prepared with a 20×20×120mm prism mould. The curing conditions of the sample are water immersion and air exposed at below 23°C.

Table 3 Parameter and level

No.	Parameter	Level			
		1	2	3	4
P1	POFA admixture percentage(wt%)	10	20	30	40
P2	Topcoat powder-to-binder ratio	0.00	0.10	0.20	0.30
P3	Water-to-binder ratio	0.6	0.8	1	1.2
P4	Latex agent content (wt%)	0	1	5	10
P5	Particle size of POFA (μm)	140	45		
P6	Curing condition	Air	Water		

2.3 EMI shielding effectiveness measurement

In this work, a Transverse Electric and Magnetic (TEM) parallel plate was connected to a network analyser (NA), through an N-type coaxial port. This device was used to measure the dielectric constant and loss factor of sample to obtain the SE. This device was custom made especially for this project [31–33]. In order to connect this TEM parallel plate with the NA, a 60° taper was used. The tapers connect one of the aluminium plates to the inner conductor of the N-type port. The SMA connector is an interface for coaxial cable with a screw N-type coupling mechanism. The outer conductor of the N-type port is connected to another aluminium plate, this can be illustrated in Fig. 1.

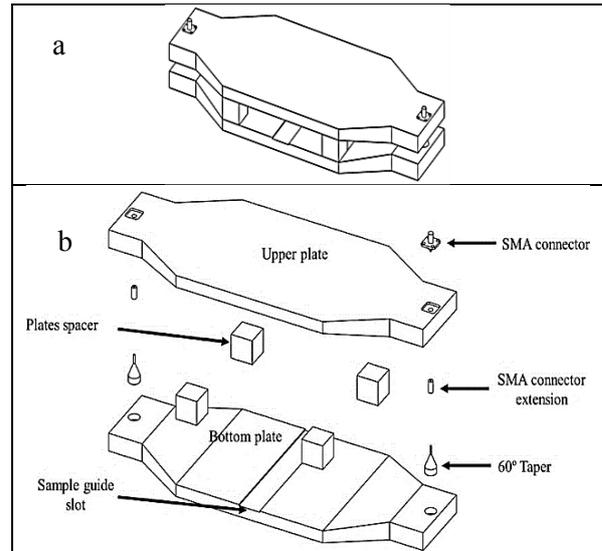


Fig. 1 TEM parallel plate (a) full assembly (b) disassembling

Based on the measured dielectric constant and loss factor of the specimen, its absorption loss (A_{dB}), reflection loss (R_{dB}), multiple reflection loss (M_{dB}) and shielding effectiveness (SE) were calculated based on equation (1)-(7)[34]. During the measurement, the sample was place between the plates at the slot.

Where,

$$SE_{dB} = A_{dB} + R_{dB} + M_{dB} \quad (1)$$

$$A_{dB} = 20 \log \left| e^{-\alpha l} \right| \quad (2)$$

$$R_{dB} = 20 \log \left| \frac{(\eta_o + \eta)^2}{4\eta_o \eta} \right| \quad (3)$$

$$M_{dB} = 20 \log \left| 1 - \left(\frac{\eta_o - \eta}{\eta_o + \eta} \right)^2 e^{-2\alpha l} \right| \quad (4)$$

$$\tan \delta = \frac{\sigma + \omega \epsilon''}{\omega \epsilon'} \quad (5)$$

$$\eta = \sqrt{\frac{j\mu_r \mu_o}{\epsilon_o \epsilon_r (LT + j)}} \quad (6)$$

$$\gamma = \sqrt{j\omega^2 \mu_o \mu_r \epsilon_o \epsilon_r (LT + j)} \quad (7)$$

Fig. 2 shows the setup of the dielectric measurement. The frequency applied is between 0.1 to 1.4 GHz accordance to the daily life EMW exposes.

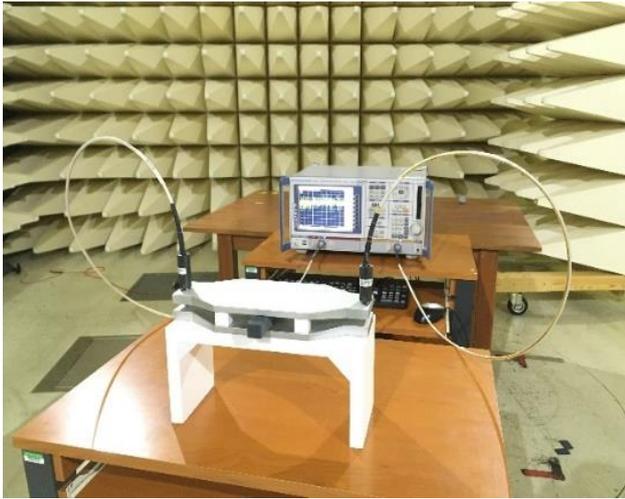


Fig. 2 TEM parallel plate setup

2.4 Taguchi design and FPA optimization method

In this study, the Taguchi design method was used to study a large number of variables with minor of experiments number. Taguchi design was chosen to optimize the preparation condition of EMI SE plaster mortar containing POFA. The six parameter that mainly use in Taguchi design are POFA admixture percentage

(wt.%), topcoat powder-to-binder ratio, water-to-binder ratio, latex agent content (wt.%), particle size of POFA (μm) and curing condition, which is chosen as factors with appropriate mix factor levels L_{16} orthogonal array table as Table 4 shown. All variables are selected based on literature and previous study [3, 8, 28, 35, 36] as well as suitability of local raw material (POFA). The normal full factorial design would require $2^2 \times 4^4 = 1024$ experiment runs. Clearly, it is very impossible to do these experimental runs and will take high in cost but while using Taguchi design can simplify only 16 runs (Table 4). In order to ascertain the direct comparison with different scales of observation, the variables were normalized between (-1, 1) by using equation (8) to explore the individual influence of each variable in determine the output response.

Where X_n is the normalized value of the parameter variables which are POFA admixture percentage (wt.%), topcoat powder-to-binder ratio, water-to-binder ratio, latex agent content (wt.%), particle size of POFA (μm) and curing condition. X is the absolute value of the actual response, \bar{X} is the mean value of X_{max} and X_{min} whereas X_{max} and X_{min} is the maximum and minimum value for a particular parameter variable, respectively. The normalized result was shown in Table 7.

Table 4 L_{16} mix level Taguchi Design and Experimental Results

Run	Parameters						Coded value						Experiment al values of EMI SE (dB)
	Actual value						X_1	X_2	X_3	X_4	X_5	X_6	
	POFA admixture (%)	TP/B ratio	W/B ratio	LA content (%)	POFA Size (μm)	Curing condition							
1	10	0	0.6	0	140	Air	-1	-1	-1	-1	-1	-1	-8
2	10	0.1	0.8	1	140	Water	-1	-0.33	-0.33	-0.33	-1	1	-5
3	10	0.2	1	5	45	Air	-1	0.33	0.33	0.33	1	-1	-5
4	10	0.3	1.2	10	45	Water	-1	1	1	1	1	1	-6
5	20	0	0.8	5	45	Water	-0.33	-1	-0.33	0.33	1	1	-6
6	20	0.1	0.6	10	45	Air	-0.33	-0.33	-1	1	1	-1	-23
7	20	0.2	1.2	0	140	Water	-0.33	0.33	1	-1	-1	1	-8
8	20	0.3	1	1	140	Air	-0.33	1	0.33	-0.33	-1	-1	-4
9	30	0	1	10	140	Water	0.33	-1	0.33	1	-1	1	-9
10	30	0.1	1.2	5	140	Air	0.33	-0.33	1	0.33	-1	-1	-7
11	30	0.2	0.6	1	45	Water	0.33	0.33	-1	-0.33	1	1	-9
12	30	0.3	0.8	0	45	Air	0.33	1	-0.33	-1	1	-1	-7
13	40	0	1.2	1	45	Air	1	-1	1	-0.33	1	-1	-7
14	40	0.1	1	0	45	Water	1	-0.33	0.33	-1	1	1	-7
15	40	0.2	0.8	10	140	Air	1	0.33	-0.33	1	-1	-1	-7
16	40	0.3	0.6	5	140	Water	1	1	-1	0.33	-1	1	-8

2.5 Flower pollination algorithm (FPA)

FPA was developed by Xin-She Yang in 2012 [37]. This algorithm method is a new nature-inspired algorithm, based on the characteristics of flowering plants [27, 37]. Flower pollination algorithm (FPA) uses the following four rules in optimization [37]:

- Biotic and cross-pollination can be considered as a process of global pollination process, and pollen-carrying pollinators move in a way which obeys Lévy flights (Rule 1).

- For local pollination, abiotic and self-pollination are used (Rule 2).
- Pollinators such as insects can develop flower constancy, which is equivalent to a reproduction probability that is proportional to the similarity of two flowers involved (Rule 3).
- The interaction or switching of local pollination and global pollination can be controlled by a switch probability $p \in [0, 1]$, with a slight bias towards local pollination (Rule 4).

The population size is 25 and 1000 of iteration number, the coding was run to develop the best result of targeted EMI SE. The pseudo code of the proposed Flower Pollination Algorithm (FPA) can represent as follows [37]:

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Objective min or max  $f(\mathbf{x})$ ,  $\mathbf{x} = (x_1, x_2, \dots, x_d)$ 
Initialize a population of  $n$  flowers/pollen gametes with random solutions
Find the best solution  $g^*$  in the initial population
Define a switch probability  $p \in [0, 1]$ 
Define a stopping criterion (either a fixed number of generations/iterations or accuracy)
while ( $t < \text{MaxGeneration}$ )
    for  $i = 1: n$  (all  $n$  flowers in the population)
        if  $\text{rand} < p$ ,
            Draw a ( $d$ -dimensional) step vector  $L$  which obeys a Lévy distribution
            Global pollination via  $x_i^{t+1} = x_i^t + L(g^* - x_i^t)$ 
        else
            Draw  $\epsilon$  from a uniform distribution in  $[0, 1]$ 
            Do local pollination via  $x_i^{t+1} = x_i^t + \epsilon(x_j^t - x_k^t)$ 
        end if
        Evaluate new solutions
        If new solutions are better, update them in the population
    end for
    Find the current best solution  $g^*$ 
end while
Output the best solution found
    
```

Fig. 3 Pseudo code of the proposed Flower Pollination Algorithm (FPA) (X.-S. Yang, 2012)

To run the FPA, a set of objective function equation must develop before running the optimization in MATLAB software. The objective function equation was developed by coded values of the experimental results using the interaction model equation as equation (9) shown.

$$Y = \beta_0 + \sum_{i=1}^k \beta_i X_i + \sum_{i < j}^k \beta_{ij} X_i X_j \tag{9}$$

where Y is the dependent variable or estimation for the response variables of the designed experiment (EMI shielding effectiveness), and b is the estimation for the regression coefficient computed by least squares approach. Finally, the complete objective function with interaction equation is as equation (10) shown.

$$SE = b(1) + b(2)X_1 + b(3)X_2 + b(4)X_3 + b(5)X_4 + b(6)X_5 + b(7)X_6 + b(8)X_1X_2X_3X_4 + b(9)X_5X_6X_1X_2 + b(10)X_3X_4X_5X_6 \tag{10}$$

3. Results and Discussion

3.1 Experimental result

The experimental dielectric measurement was successfully done by using TEM parallel plate. The calculation was done based on equation (1) to equation

(7) via Microsoft excel. Based on the Taguchi design, the results were fluctuated from number 1 to number 16 of experiment run. The best EMI shielding effectiveness (SE) was shows on number 6 of L_{16} Taguchi design which is achieved -23dB SE (Fig. 4 and Fig. 5). In run number 6, the POFA admixture percentage (wt.%) is 20%, topcoat powder-to-binder ratio is 0.1, water-to-binder ratio is 0.6, with latex agent content (wt.%) of 10%, the particle size of POFA (μm) is $45\mu\text{m}$ and with air curing condition. The EMI SE is dependent on POFA admixture (X_1) and the particle size of POFA (X_5) as shown in Table 7. Based on P. Chindapasirt [8] work, the ideal water-to-binder ratio is in between 0.6 to 0.75, while in this study the experimentally data shows that 0.6 is the best water-to-binder ratio.

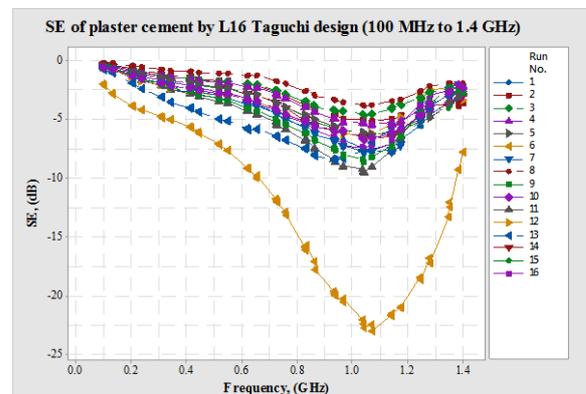


Fig. 4 SE of plaster cement by L16 Taguchi design (100 MHz to 1.4 GHz)

In P. Chindapasirt [8] work have stated that by using a better grade/finer fly ash or by incorporation of plasticizer/agent can improve the mechanical properties of plastering mortar which can minimized the water retention. In this study, an Ultra-fined POFA with below $45\mu\text{m}$ particle size would increase the EMI SE due to the smaller particle size can retain the EMW inside the plaster mortar prism. Meanwhile, the higher percentage of latex agent can act as water retainer similarly with plasticizer characteristic as P. Chindapasirt[8] plastering work. The curing condition also is one of importance variables to influenced the EMI SE. The plaster mortar prism with air curing condition shows better SE due to the completely dry plaster mortar prism can vacate the structure of plaster mortar to absorbing and reflecting the EMW wave well. Besides that, topcoat coat powder can improve 10% of the EMI SE due to its containing high limestone which can improve the water retention.

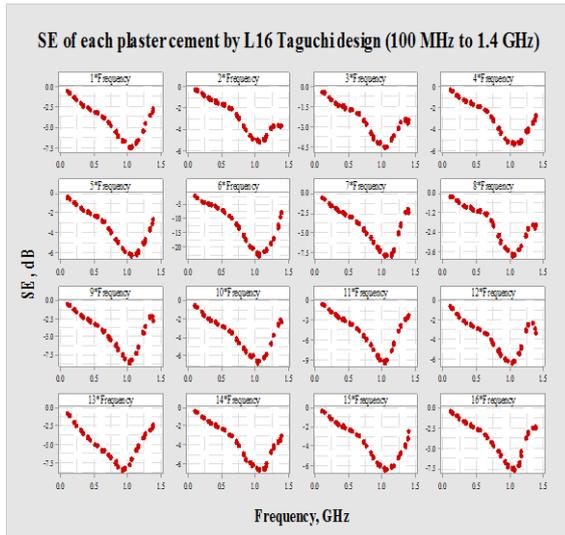


Fig. 5 SE of each plaster cement by L16 Taguchi design (100 MHz to 1.4 GHz)

3.2 Interaction Modelling

The FPA was used to obtain the best solution to approaching the higher EMI SE. At the same time, Table 5 shows the regression statistics result which is R square is equal to 0.674192542. The closer to 1 of R square is consider as a very good fit. To verify the reliable of parameter variables, the significant F must equal or less than 0.05. In Table 6, the analysis of variance (ANOVA) are statistically insignificant due to significant F value greater than 0.05. But in this case, the investigations on EMI SE of plaster mortar still consider all variables in modelling equation. Base on the Table 7, the sign and magnitude of regression coefficient signify the relative influence of each parameter of the output response (EMI SE) with a negative sign indicating an antagonistic effect whilst a positive one signifies a synergistic effect. The mathematical interaction model of EMI SE of POFA layer 1 was developed based on the sign and magnitude of regression coefficient as shown in equation (11).

The FPA can improve the prediction SE at 6.86% compare to experimental result. The summary of comparison is shows in Table 7. Based on P-value coefficient of mathematical interaction model in Table 8, EMI SE is mainly dependent on the four interaction

between $X_3X_4X_5X_6$ (water-to-binder ratio, latex agent content, particle size of POFA, curing condition) followed by POFA admixture percentage (X_1), $X_5X_6X_1X_2$ (POFA admixture percentage, topcoat powder-to-binder ratio, particle size of POFA, curing condition), particle size of POFA (X_5), latex agent content (X_4), $X_1X_2X_3X_4$ (POFA admixture percentage, topcoat powder-to-binder ratio, water-to-binder ratio, latex agent content), topcoat powder-to-binder ratio (X_2), water-to-binder ratio (X_3) and curing condition (X_6).

Table 5 Regression statistic

Regression Statistics	
Multiple R	0.821092286
R Square	0.674192542
Adjusted R Square	0.185481354
Standard Error	3.855511028
Observations	16

Table 6: ANOVA

	df	SS	MS	F	Significance F
Regression	9	184.56	20.51	1.38	0.36
Residual	6	89.19	14.86		
Total	15	273.75			

$$SE = (-6.886) + (-1.412) X_1 + (0.962) X_2 + (0.801) X_3 + (-4.645) X_4 + (-1.680) X_5 + (0.186) X_6 + (-10.866) X_1X_2X_3X_4 + (5.268) X_5X_6X_1X_2 + (-4.449) X_3X_4X_5X_6 \quad (11)$$

Finally, the FPA gives the best solution for approaching the higher EMI SE as follow: 30.012% of POFA admixture percentage, 0.3 of topcoat powder-to-binder ratio, 1.03 of water-to-binder ratio, 10% of latex agent content, 45µm particle size of POFA and air curing condition. The FPA can obtain up to -24.68 dB of EMI SE while the experimental results can obtain only -23dB.

Table 7: Comparison of SE between FPA Optimization and experimental data

Method	POFA admixture (%)	TP/B ratio	W/B ratio	LA content (%)	POFA Size (µm)	Curing condition	EMI SE (dB)	Improvement (%)
Taguchi	20	0.1	0.6	10	45	Air	-23	
FPA	30.012	0.3	1.03	10%	45	Air	-24.68	6.86

Table 8: Coefficient of mathematical interaction model

Variables	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	-6.886	1.067	-6.456	0.001	-9.496	-4.276	-9.496	-4.276
X ₁	-1.412	1.405	-1.005	0.354	-4.848	2.025	-4.848	2.025
X ₂	0.962	4.697	0.205	0.844	-10.532	12.457	-10.532	12.457
X ₃	0.801	3.906	0.205	0.844	-8.756	10.358	-8.756	10.358
X ₄	-4.645	8.526	-0.545	0.606	-25.507	16.218	-25.507	16.218
X ₅	-1.680	2.263	-0.742	0.486	-7.217	3.857	-7.217	3.857
X ₆	0.186	3.014	0.062	0.953	-7.190	7.562	-7.190	7.562
X ₁ X ₂ X ₃ X ₄	-10.866	27.641	-0.393	0.708	-78.500	56.769	-78.500	56.769
X ₅ X ₆ X ₁ X ₂	5.268	6.774	0.778	0.466	-11.307	21.844	-11.307	21.844
X ₃ X ₄ X ₅ X ₆	-4.449	2.056	-2.164	0.074	-9.481	0.582	-9.481	0.582

4. Summary

This study mainly deals with Taguchi design of experimental investigation and FPA optimization in EMI shielding effectiveness of plaster mortar. However, the use of L₁₆ Taguchi design can minimize hundreds of experiment runs and at the same time the use of FPA also can obtain the optimum solution. Mathematical interaction model of EMI SE in terms of all parameter variables have been developed using regression analysis and checked for its adequacy. By using Matlab software, the model developed was inserted into FPA command to develop the optimal parameter variable for targeted EMI SE. The following conclusions were drawn from the results of this investigation.

- The used of Taguchi design can be conclude that is very satisfactory for this experiment. It is highly recommended for other researcher to use the Taguchi method for design their experiment for more efficiency of research work.
- The Taguchi method provided appropriate design for this experiment even though the level of control factor is various and mixed.
- From the experimental results, the mixing 20% of POFA can be shield the EMW at -23dB while FPA can predicted up to -24.68dB.
- From mathematical intersection model, the EMI SE is mainly dependent on POFA admixture percentage (X₁) followed by particle size of POFA (X₅), latex agent content (X₄), topcoat powder-to-binder ratio (X₃), water-to-binder ratio and curing condition (X₆).
- In terms of interaction between four parameters, the EMI SE is mainly dependent on X₃X₄X₅X₆ (water-to-binder ratio, latex agent content, particle size of POFA, curing condition) followed by, X₅X₆X₁X₂ (POFA admixture percentage, topcoat powder-to-binder ratio, particle size of POFA, curing condition) and X₁X₂X₃X₄ (POFA admixture percentage, topcoat powder-to-binder ratio, water-to-binder ratio, latex agent content).
- FPA suggested optimum parameter variables to approaching higher EMI SE as follow: 30.012% of POFA admixture percentage, 0.3 of topcoat powder-

to-binder ratio, 1.03 of water-to-binder ratio, 10% of latex agent content, 45µm particle size of POFA and air curing condition.

- The optimal variables obtained from FPA listed limited for the single objective only which is approaching higher EMI SE.
- The FPA can obtain 6.68% higher EMI SE based the suggested optimal parameter variables.

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References

- [1] Beall, C. et al. Brain tumors among electronics industry workers. *Epidemiology*, Volume 7(2), (1996), pp. 125–130.
- [2] Xie, S. et al. Development of layer structured wave absorbing mineral wool boards for indoor electromagnetic radiation protection. *Journal of Building Engineering*, Volume 5, (2016), pp. 79–85.
- [3] Narong, L.C. et al. Optimization of the EMI shielding effectiveness of fine and ultrafine POFA powder mix with OPC powder using Flower Pollination Algorithm. *IOP Conference Series: Materials Science and Engineering*. IOP Publishing, Volume 165(1), (2017), pp. 12035-12047.
- [4] Baoyi, L. et al. The electromagnetic characteristics of fly ash and absorbing properties of cement-based composites using fly ash as cement replacement. *Construction and Building Materials*, Volume 27(1), (2012), pp. 184–188.
- [5] Cao, J., Chung, D.D.L. Coke powder as an admixture in cement for electromagnetic interference shielding. *Carbon*, Volume 41(12), (2003), pp. 2433–2436.
- [6] Kimura, K., Hashimoto, O. Three-layer wave absorber using common building material for wireless LAN. *Electronics Letters*, Volume 40 (21), (2004), pp. 1323-1324.
- [7] Huang, L., Ding, S. Experimental and numerical analyses of electromagnetic attenuation properties of an L-shaped channel constructed by electromagnetic

- absorbing concrete. In: *Computational Science and Optimization (CSO), 2010 Third International Joint Conference on. IEEE*, Volume 1, (2010), pp. 335–338.
- [8] Chindaprasirt, P. Mixed cement containing fly ash for masonry and plastering work. Volume 19, (2005), pp. 612–618.
- [9] Guan, H. et al. Cement based electromagnetic shielding and absorbing building materials. *Cement and Concrete Composites*, Volume 28 (5), (2006), pp. 468–474.
- [10] Chung, D.D.L. Materials for electromagnetic interference shielding. *Journal of Materials Engineering and Performance*, Volume 9 (3), (2000), pp. 350–354.
- [11] Khalid, N.H.A. et al. Palm oil fuel ash as potential green micro-filler in polymer concrete. *Construction and Building Materials*, Volume 102, (2016), pp. 950–960.
- [12] ASTM C618. Standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete. *American society for testing and materials. West Conshohocken, PA, USA: ASTM International*, Volume 12, (2012), pp. 1-3.
- [13] Khankhaje, E. et al. On blended cement and geopolymer concretes containing palm oil fuel ash. *Materials & Design*, Volume 89, (2015), pp. 385–398.
- [14] Sia, C.K. et al. Optimum preparation and thermal conductivity of novel glossy paint prepared from waste of palm oil fly ash composite. *International Journal of Automotive & Mechanical Engineering*, Volume 12, (2015), pp. 3058-3064.
- [15] Lim, S.K. et al. Fresh and hardened properties of lightweight foamed concrete with palm oil fuel ash as filler. *Construction and Building Materials*, Volume 46, (2013), pp. 39–47.
- [16] Zainudin, A. et al. Taguchi design and flower pollination algorithm application to optimize the shrinkage of triaxial porcelain containing palm oil fuel ash. In: *IOP Conference Series: Materials Science and Engineering. IOP Publishing*, Volume 165, (2017), pp. 12036-12043.
- [17] Kroehong, W. et al. Effect of palm oil fuel ash fineness on packing effect and pozzolanic reaction of blended cement paste. *Procedia Engineering*, Volume 14, (2011), pp. 361–369.
- [18] Tanyildizi, H., Şahin, M. Application of Taguchi method for optimization of concrete strengthened with polymer after high temperature. *Construction and Building materials*, Volume 79, (2015), pp. 97–103.
- [19] Hınıslioğlu, S., Bayrak, O.Ü. Optimization of early flexural strength of pavement concrete with silica fume and fly ash by the taguchi method. *Civil Engineering and Environmental Systems*, Volume 21(2), (2004), pp. 79–90.
- [20] Türkmen, İ.m et al. Determination by the Taguchi method of optimum conditions for mechanical properties of high strength concrete with admixtures of silica fume and blast furnace slag. *Civil Engineering and Environmental Systems*, Volume 20(2), (2003), pp. 105–118.
- [21] Ozbay, E. et al. Investigating mix proportions of high strength self-compacting concrete by using Taguchi method. *Construction and Building materials*, Volume 23 (2), (2009), pp. 694–702.
- [22] Türkmen, İ. et al. A Taguchi approach for investigation of some physical properties of concrete produced from mineral admixtures. *Building and Environment*, Volume 43(6), (2008), pp. 1127–1137.
- [23] Olivia, M., Nikraz, H. Properties of fly ash geopolymer concrete designed by Taguchi method. *Materials & Design*, Volume 36, (2012), pp. 191–198.
- [24] Chang, C.Y. et al. Application of a weighted Grey-Taguchi method for optimizing recycled aggregate concrete mixtures. *Cement and concrete composites*, Volume 33(10), (2011), pp. 1038–1049.
- [25] Bagheri, A., Nazari, A. Compressive strength of high strength class C fly ash-based geopolymers with reactive granulated blast furnace slag aggregates designed by Taguchi method. *Materials & Design*, Volume 54, (2014), pp. 483–490.
- [26] Huang, M.-L. et al. Validation of a method using Taguchi, response surface, neural network, and genetic algorithm. *Measurement*, Volume 94, (2016), pp. 284–294.
- [27] Yang, X. S. *Flower pollination algorithm for global optimization*. In: *International Conference on Unconventional Computing and Natural Computation*. Springer, Volume 7445, (2012), pp. 240–249.
- [28] Ching, N.O.L. et al. Exploring the Potential of Palm Oil Fuel Ash (POFA) in EMI Shielding Effectiveness. *International Journal of Mechanical Engineering*, Volume 2(1), (2017), pp. 101-111.
- [29] ASTM C144. Standard Specification for Aggregate for Masonry Mortar 1. *American society for testing and materials. West Conshohocken, PA, USA: ASTM International*, Volume 70, (2014), pp. 53–54.
- [30] ASTM C91. Masonry Cement 1. *American society for testing and materials. West Conshohocken, PA, USA: ASTM International*, Volume 4, (2003), pp. 1–6.
- [31] Yee, S.K. et al. Prediction of Shielding Effectiveness of Cement-Graphite Powder Using Artificial Neural Network. *Jurnal Teknologi*, Volume 78(6-2), (2016), pp. 33-38.
- [32] Yee, S.K. et al. Design and calibration of a wideband TEM-cell for material characterization. In: *Electromagnetic Compatibility (APEMC), 2012 Asia-Pacific Symposium on. IEEE*, Volume 10, (2012), pp. 749–752.
- [33] Wilson, P.F., Ma, M.T. Techniques for Measuring the Electromagnetic Shielding Effectiveness of Materials: Part II-Near-Field Source Simulation. *IEEE Trans. Electromag. Compat.*, Volume 30(3), (1988), pp. 251–259.

- [34] Paul, C.R. Introduction to electromagnetic compatibility. *John Wiley & Sons*, Volume 184, (2006), pp. 1-48.
- [35] Sinsiri, T. et al. Assessing the effect of biomass ashes with different finenesses on the compressive strength of blended cement paste. *Materials and Design*, Volume 42, (2012), pp. 424–433.
- [36] Tangchirapat, W. et al. Use of palm oil fuel ash as a supplementary cementitious material for producing high-strength concrete. *Construction and Building Materials*, Volume 23(7), (2009), pp. 2641–2646.
- [37] Yang, X.S. et al. Multi-objective flower algorithm for optimization. *Procedia Computer Science*, Volume 18, (2013), pp. 861–868.