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# Building Energy Efficiency: Optimization of Building Envelope Using Grey-Based Taguchi

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***Abstract*—Buildings sector currently consume the heights share of end-use energy in most countries. Thus, it would be beneficial for residential communities to minimize energy loss/gain from buildings envelopes. This can be done by optimizing physical properties of construction building materials. In this study, the $L_9$ orthogonal array is selected with 3-levels and 4-factors, namely: wall thickness, density, thermal conductivity, and specific heat. Single response optimization is performed using Taguchi method. However, materials performance for energy consumption depends on many quality characteristics, which cannot be resolved by Taguchi method. An application of the grey-based Taguchi technique can be used for multi-responses optimization, which combines the Taguchi DOE with grey relational analysis to find the grey relational grade that can convert the optimization of multi responses into single quality optimization. This quality is used to determine optimal factors level on heating, cooling energy consumption and thermal diffusivity. Analysis of variance is employed to determine the influence percentage contribution of these factors. The heating and cooling energy consumptions are calculated using EnergyPlus simulation software. The obtained results identify the optimum specifications of lightweight concrete blocks from energy consumption point of view. The optimum lightweight concrete blocks have shown to reduce energy consumption when compared to normal weight concrete blocks by 19%. Also, the results show that the conductivity is the most influential factor on energy transmitted through building walls with 80.62% contribution and wall thickness with 17.03%, followed by density and specific heat for this set of experiments.**

***Keywords—lightweight concrete; design of experiment; simulation; heating and cooling energy use***

## I. Introduction

The demand for low energy consumption for residential housing and industrial buildings constructions have led engineers and researchers to improve existing lightweight materials and/or develop new ones, such as lightweight aggregate concrete with high strength-to-weight ratio and low heat absorption which makes it very attractive structural materials for domestic housing, industrial and commercial buildings than normal weight concrete. It is most important for the communities to reduce the energy consumption and carbon emission. Energy consumption for both residential and commercial buildings in developed countries account for 20% to 40% of total energy used [1], while it accounts for more than 40% of total energy used in some developing countries [2]. Lee J.W et al. [3] reported that the energy consumption for residential building is mainly used for lighting and space heating and cooling.

Energy consumption for residential and commercial buildings made of lightweight concrete blocks can be optimized for single quality using Taguchi Design of Experiment(DOE)[4]. Taguchi design of experiment makes the use of orthogonal arrays to minimize the number of parameters combinations that are required to test the parameter effects and can be performed at a lowered cost and time with results comparable to a full factorial experiment.

Grey relational analysis can handle both incomplete information and unclear problems more precisely. The grey relational analysis [5-7] can convert the optimization of multiple quality characteristics into a single quality optimization called grey relational grade, which can provide optimum process parameters. Hatab et al. [8-10] investigated the effects of process parameters on properties of various materials using Grey based Taguchi.

The aim of this study is to investigate the influence of lightweight concrete blocks factors, namely wall thickness, density, thermal conductivity, and specific heat, on heating and cooling loads and thermal diffusivity using Grey-based Taguchi optimization method.

## II. Design of Experiment

The specifications of lightweight concrete blocks may be optimized by using Taguchi design of experiments [4]. The wall thickness, density, thermal conductivity and specific heat are considered factors of the lightweight aggregate concrete of buildings blocks that influence the heating, cooling energy consumptions and thermal diffusivity. A standard Taguchi DOE of the $L_9$ ($3^4$) orthogonal arrays is selected, and the interactions between the factors are neglected. Table 1 and Table 2 show experiments, factors, and their levels and layout of the $L_9$ ($3^4$) orthogonal arrays. The next steps in Taguchi DOE are to run the experiments and then to evaluate the results of experiments to determine the main effects of factors and to find the optimum condition and then applying analysis of variance (ANOVA) to determine the contribution of the affected factors on the quality response.

TABLE 1 - FACTORS AND LEVELS FOR TAGUCHI DOE OF THE $L_9$ ORTHOGONAL ARRAYS

| Factors | Level 1 | Level 2 | Level 3 |
|---|---|---|---|
| **A** Wall thickness, mm | 150 | 200 | 300 |
| **B** Density, kg/m$^3$ | 1200 | 1360 | 1440 |
| **C** Conductivity, W/m.$^o$K | 0.3 | 0.5 | 0.9 |
| **D** Specific heat, J/kg.$^o$K, | 840 | 860 | 880 |

TABLE 2 - EXPERIMENTAL LAYOUT OF ORTHOGONAL ARRAYS $L_9$ ($3^4$) FOR TAGUCHI DOE

| Experiment Number | A | B | C | D |
|---|---|---|---|---|
| 1 | 150 | 1200 | 0.3 | 840 |
| 2 | 150 | 1360 | 0.5 | 860 |
| 3 | 150 | 1440 | 0.9 | 880 |
| 4 | 200 | 1200 | 0.5 | 880 |
| 5 | 200 | 1360 | 0.9 | 840 |
| 6 | 200 | 1440 | 0.3 | 860 |
| 7 | 300 | 1200 | 0.9 | 860 |
| 8 | 300 | 1360 | 0.3 | 880 |
| 9 | 300 | 1440 | 0.5 | 840 |

There are three categories to describe the quality characteristics (response): lower-is-better (LB), nominal-is-better (NB), and higher-is-better (HB). In this study, heating and cooling energy consumption and thermal diffusivity treated as a quality response, and hence the lower-is-better (LB) characteristic is used for minimizing the energy consumption.

EnergyPlus simulation software is employed to calculate the responses namely heating and cooling consumptions required to maintain the zone at preset setpoints conditions. Heating set-point is 21°C from 07:00 – 19:00, and 15.6°C for the rest of the day, while cooling set-point is 24°C from 07:00 – 19:00, and 26.7°C for the rest of the day. The used materials are lightweight concrete blocks with two cores for construction of external wall of a room with an area of 16.0 m$^2$ (the room dimension is 4 x 4 x 4 meter). The properties of the materials are obtained from ASHRAE handbook: Fundamentals[11]. For the analysis, all opaque building components of the office room are considered as adiabatic, with the exception of the wall under study. The weather data (local region) used in the simulation is obtained from EnergyPlus website. The “Ideal Loads Air System” is used in order to estimate the energy consumption of the room without modeling a full HVAC system, which is considered as an ideal unit that operates at 100% efficiency in order to meet the specified controls.

## III. RESULTS AND DISCUSSION

### A. *Single Response*

Figures 1, 3, and 5 show the experimental results for heating, cooling energy consumptions, and thermal diffusivity respectively. It is evident from the obtained results that experiment number 8 for heating and cooling give the lower energy consumptions and experiment number 6 gives the lower thermal diffusivity among the nine running experiments. Experiment number 8 runs at levels of 300 mm wall thickness, 1360 kg/m$^3$ density, 0.3 W/m.$^o$K thermal conductivity, and 880 J/kg.$^o$K specific heat, while experiment number 6 runs at levels of 200 mm wall thickness, 1440 kg/m$^3$ density, 0.3 W/m.$^o$K thermal conductivity, and 860 J/kg.$^o$K specific heat . It is clearly indicated that experiment number 8 takes longer time for heat to diffuse in or out of the unit volume that will cause a change of the temperature and thus lower energy consumption is a result, compared to experiment number 3.

The responses data for average effects shown in Figures 2, 4 and 6 indicate that the most influential factor is conductivity, followed by wall thickness, density and the least influential factor is specific heat.

### B. *Multiple Response*

In the grey relational analysis [6,7], the data preprocessing must be performed first (generation of grey relation) in order to normalize the experimental results in the range of zero to one. In this investigation, the values of responses are normalized for the lower-is-better quality response; and the calculated response is given by equation (1):

$$(x_{ij})_{LB} = \frac{X_{max} - X_{ij}}{X_{max} - X_{min}} \tag{1}$$

Where $x_{ij}$ is the normalized value for the $j^{th}$ performance quality in the $i^{th}$ experimental run. $X_{ij}$ is the response value for the $j^{th}$ performance quality in the $i^{th}$ experimental run. $X_{min}$ and $X_{max}$ are the minimum and the maximum of the response values for the $j^{th}$ performance quality in all the experimental runs. Table 3 shows the $x_{ij}$ response (data preprocessing). The higher value of the $x_{ij}$ is considered the best performance for the energy consumption and thermal diffusivity compared to the ideal value of one. After calculating the $x_{ij}$, then the grey relational coefficient ($\xi_{ij}$) is determined using equation (2):

$$\xi ij = \frac{\min_i \min_j | x_i^o - x_{ij} | + \beta * \max_i \max_j | x_i^o - x_{ij} |}{| x_i^o - x_{ij} | + \beta * \max_i \max_j | x_i^o - x_{ij} |} \tag{2}$$

Where $x_i^0$ is the ideal normalized value for the $j^{th}$ performance quality in the $i^{th}$ experimental run, and $\beta$ is the distinguish coefficient which is defined in the range $0 \leq \beta \leq 1$. The general used value for $\beta$ is 0.5. Note that the $\xi_{ij}$ is to express the relationship between the ideal and the actual $x_{ij}$ of the experimental results.

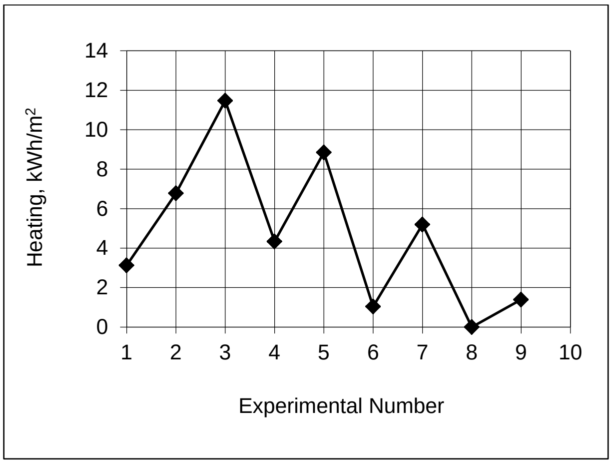


Fig. 1. Calculated heating energy consumption by EnergyPlus simulation for lightweight concrete

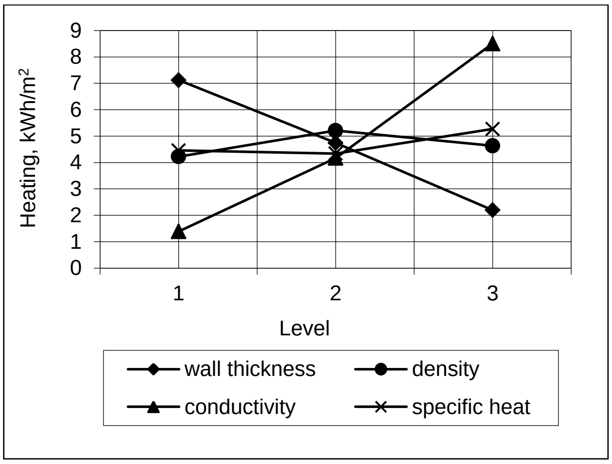


Fig. 2. Effects of parameters on mean heating energy consumption of lightweight concrete

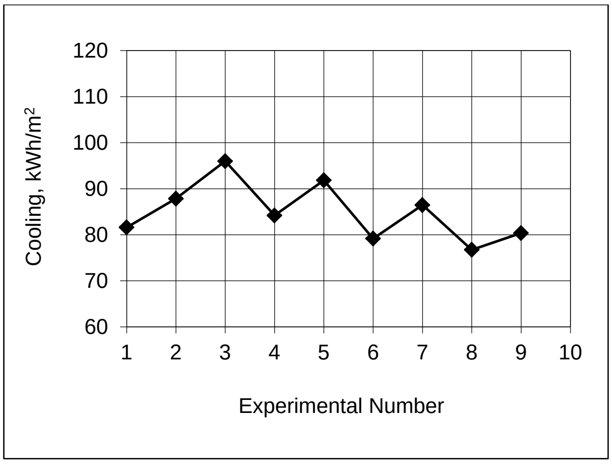


Fig. 3. Calculated cooling energy consumption by EnergyPlus simulation for lightweight concrete

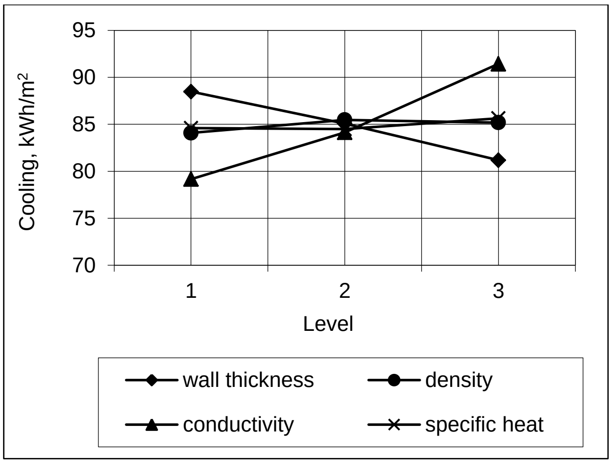


Fig. 4. Effects of parameters on mean cooling energy consumption of lightweight concrete

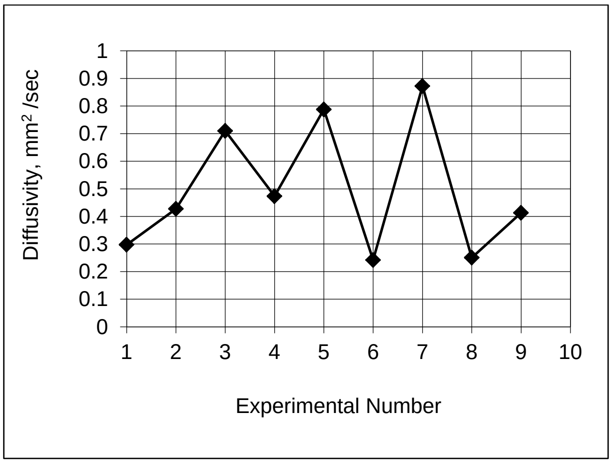


Fig. 5. Calculated thermal diffusivity by Equation (α = k/ρc) for lightweight concrete

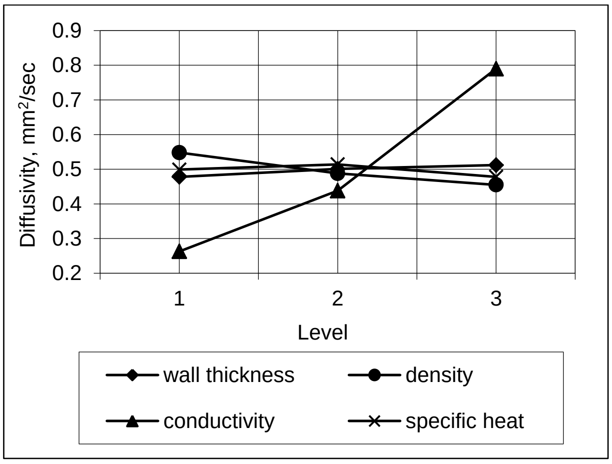


Fig. 6. Effects of parameters on mean thermal diffusivity for lightweight concrete

After determining the $\xi_{ij}$, the weighting method is used to determine the grey relational grade ( Γ), and is given by equation (3):

$$\Gamma = \frac{1}{n}\sum_{i=1}^{n} w_i \times \xi_{ij} \quad (3)$$

Where $w_i$ is the weighting factor for the $j^{th}$ performance quality, and $n$ is the number of performance. In the present study, the weighting factor for heating and thermal diffusivity is given a value of 0.25 and cooling is taken as 0.5. The results are shown in Table 3. The effects of each physical property variables are determined using the grey relational grade at various levels. Table 4 and Figure 7 show the grey relational grade response data. Based on the results in Tables 3, 4 and Figure 7 that indicate experiment number 8 has the best combination of physical properties for energy consumption saving and thermal diffusivity. The optimal physical properties are level 3 for wall thickness, level 3 for density, level1 for conductivity and level 3 for specific heat or A3B3C1D3, and the most significant influential parameter on energy consumption savings and thermal diffusivity is the thermal conductivity, followed by wall thickness while the least influential parameters are the density and specific heat as shown in Table 4 and Figure 7.

### *C. Analysis of variance (ANOVA) for Multiple Response*

The ANOVA [4] can be accomplished base on the total sum of the squares deviations from the total mean of the grey relational grade (Γ). The total sum of the squares is decomposed into the sum of squares due to each tested factor and the sum of squares due to the error. The percentage of the contribution for each physical property in the total sum of squared deviation is employed to determine the most important physical property that affects the performance characteristics. The ANOVA results given in Table 5 show that thermal conductivity is the most significant physical property for energy consumption saving with 80.62% contribution followed by wall thickness with 17.03% and then the density with 1.87% and specific heat with 0.48%. Thus, the optimal properties of lightweight concrete blocks are 300mm wall thickness, 1440 kg/m$^3$ density, 0.3 W/m.$^o$K thermal conductivity and 880 J/kg.$^o$K specific heat, A3B3C1D3, which is consistent with experiment 8 shown in Table 2.

### *D. Confirmation Test*

The confirmation of experiment is the final step to verify the multiple quality characteristics using the optimal levels of the physical properties of lightweight concrete blocks for energy consumption savings. If the results of the confirmation test do not agree with the results of the experiment runs, then new experiments are required. The predicted grey relational grade ($\Gamma$) for optimizing energy consumptions is given by equation (4):

$$\Gamma_{conf} = \Gamma_{mean} + \sum_{i=1}^{n}[(\Gamma_{opt})_i - \Gamma_{meam}] \quad (4)$$

A comparison between running experiment confirmation (A3B3C1D3) predicted by equation (4) and running experiment number 8 that has the best combination of physical properties (A3B2C1D3) are shown in Table 6. The two cases have the same energy consumption of 76.73 kWh/m2 and could provide 19% energy saving when compared to normal weight concrete blocks.

TABLE 3. NORMALIZED VALUES ($x_{ij}$) AND CALCULATED GREY RELATIONAL GRADE.

| Experiment numbers | Heating $x_{ij}$ | Cooling $x_{ij}$ | Diffusivity $x_{ij}$ | grey relational grade, ( Γ) | orders |
|---|---|---|---|---|---|
| **ideal** | 1.0000 | 1.0000 | 1.0000 | ------ | -- |
| **1** | 0.7271 | 0.7473 | 0.9121 | 0.7050 | 4 |
| **2** | 0.4089 | 0.4230 | 0.7058 | 0.5041 | 6 |
| **3** | 0.0000 | 0.0000 | 0.2570 | 0.3506 | 9 |
| **4** | 0.6216 | 0.6124 | 0.6328 | 0.5681 | 5 |
| **5** | 0.2284 | 0.2159 | 0.1338 | 0.3845 | 8 |
| **6** | 0.9093 | 0.8734 | 1.0000 | 0.8606 | 2 |
| **7** | 0.5466 | 0.4951 | 0.0000 | 0.4632 | 7 |
| **8** | 1.0000 | 1.0000 | 0.9866 | 0.9935 | 1 |
| **9** | 0.8788 | 0.8111 | 0.7284 | 0.7261 | 3 |

TABLE 4. GREY RELATIONAL GRADE RESPONSE ($\Gamma$)DATA.

| Factors | Level 1 | Level 2 | Level 3 | Max. – Min. | Rank |
|---|---|---|---|---|---|
| A: Wall thickness | 0.5199 | 0.6044 | 0.7278 | 0.2079 | 2 |
| B: Density | 0.5788 | 0.6274 | 0.6458 | 0.0670 | 3 |
| C: Conductivity | 0.8530 | 0.5994 | 0.3994 | 0.4536 | 1 |
| D: Specific heat | 0.6052 | 0.6093 | 0.6374 | 0.0322 | 4 |
| Total mean value of grey relational grade = 0.6173 | | | | | |

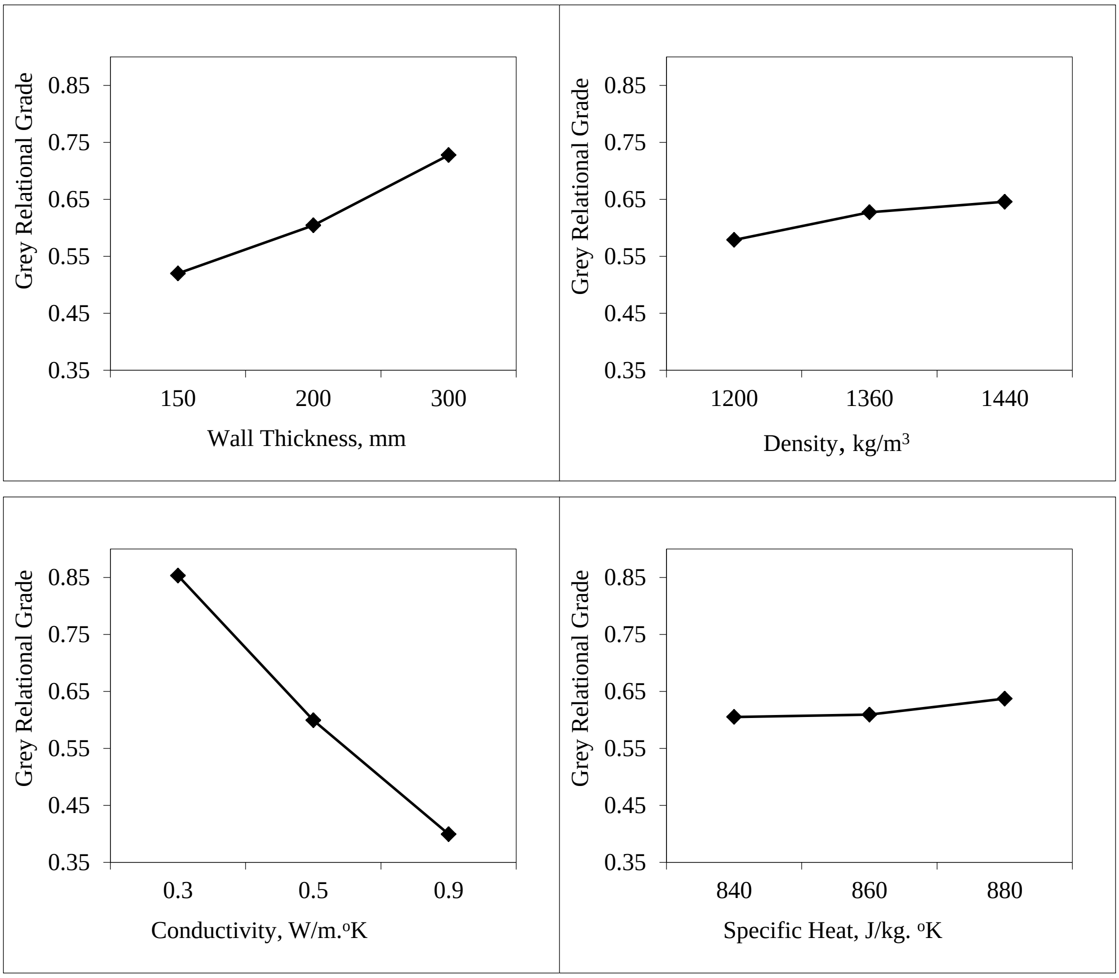


FIGURE 7. GREY RELATIONAL GRADE VS. PHYSICAL PROPERTIES LEVELS

TABLE 5. RESULTS OF THE ANOVA FOR GREY RELATIONAL GRADE OF ENERGY CONSUMPTION

| Factors | Degree of Freedom | Sum of Squares | Variance | Percent Contribution |
|---|---|---|---|---|
| A: Wall thickness | 2 | 0.0655 | 0.03275 | 17.03 |
| B: Density | 2 | 0.0072 | 0.00036 | 1.87 |
| C: Conductivity | 2 | 0.3101 | 0.15505 | 80.62 |
| D: Specific heat | 2 | 0.0018 | 0.0009 | 0.48 |
| Total | 8 | 0.3846 | -------- | 100 |

TABLE 6 - RESULTS OF CONFIRMATION TEST AND COMPARISON OF RESPONSE PERFORMANCE AT OPTIMAL LEVELS.

| Condition | level | Heating Consumption, ($kWh/m^2$) | Cooling Consumption, ($kWh/m^2$) | Thermal Diffusivity, ($mm^2/sec$) | Grey Relational Grade ( Γ) |
|---|---|---|---|---|---|
| **Prediction** | A3B3C1D3 | 0.0 | 79.36 | 0.2172 | 1 |
| **Experiment** | A3B2C1D3 | 0.0 | 76.73 | 0.2506 | 0.9935 |
| **Experiment confirmation** | A3B3C1D3 | 0.0 | 76.73 | 0.2506 | |
| **Reference*** | | 9.73 | 94.63 | 0.5693 | |
| **Improvement**** | | - 9.73 | - 17.90 | - 0.3187 | |

* Normal weight concrete blocks, 200mm wall thickness, 2100 $kg/m^3$ density, 1.1 W/m.°K conductivity, 920 J/kg.°K specific heat.

** The obtained result of the optimum is compared to reference condition

## IV. CONCLUSIONS

In this study, the optimization of multi responses namely: heating energy consumption, cooling energy consumption, and thermal diffusivity affected by physical properties of lightweight concrete blocks can be determined more precisely by using Grey-based Taguchi method. Experiment number 8 (A3B2C1D3) gives the best running experiment for improving heating and cooling energy consumptions and thermal diffusivity among the nine running experiments. The optimum levels are 300 mm wall thickness, 1440 kg/$m^3$ density, 0.3 W/m.$^o$K for conductivity, and 880 J/kg.$^o$K for specific heat (A3B3C1D3). The obtained results indicate that the most significant factors are conductivity which contributes 80.62%, followed by wall thickness with 17.03% contribution, while the least significant are density followed by the specific heat. The predicted equation can be used to determine the heating and cooling energy consumptions for any other combinations of factors in this set of experiments. The optimum lightweight blocks identified in this study may save 19% of HVAC energy consumption compared to a normal weight concrete blocks.

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