Optimization of the thermal performance of compressed earth block wall for affordable housing

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Abstract

Lack of appropriate affordable housing is a great challenge in most developing countries. Afghanistan is one of them, where in the capital, Kabul, population growth very rapidly; this resulted in a high demand for low-cost housing, construction of illegal houses and private modern townships. This has dramatically changed the form of the housing and view of the city. One of the solutions to overcome this high housing demand is to use the local material that has been used for years, traditionally. It is environmentally friendly and easily available on the construction sites. In a previous paper, three soils of the Kabul region were studied and the best earthen element was selected. In this paper, an architectural model from the selected element for Kabul climate will be developed, and analysed. According to the Köppen climate classification, Kabul has cold desert climate, with dry cold winter and dry warm summer. This study, optimize design strategy for affordable housing program, in Kabul city. Compressive earth block (CEB) walls in various thicknesses (100-1000) mm designed and thermally analysed to find the optimum wall thickness. Soil-straw plaster applied to protect the CEB wall from rain and environmental impact. Auto desk (Revit and Archiwizard) and WUFI pro software are used to optimize the wall thickness and validate the energy demand and the thermal performance of the prototype model. This research paper will enable the architects and builders to practically design earth buildings and optimize the earthen wall's thickness.

Key words: *earth construction, optimization, CEB, design strategies*

1. Introduction

The development of modern methodology for building with earth regained the interest of researchers and developers. It is due to their availability, recyclability and low embodied energy, rammed earth requires 15-25% less energy compares to fired brick [12]. Manufacturing and transportation accounts for 35% of the embodied energy of the materials [15] which is not associated with earthen elements. Soil has less embodied energy, economic, environmentally friendly and without any transportation cost [6]. Soil has great volume heat capacity and the ability to damp and delay thermal conduction and external temperature flow to the interior [8], leading to a time lag. The process in which the exterior walls react against period of delay before outside temperature reach the interior of a room is known as time lag. This high thermal capacity and density of the soil lead to: 1) absorption of humidity in a room when it is surplus and release when there is lack of it [11] and 2) absorption of heat during the day and release it when the weather is cold at nights [15].

Though, soil has average thermal property but not all the important characteristics that soil is claimed for. Earthen elements do not simply have better thermal performance than conventional concrete, and cannot guarantee thermal comfort and energy saving unless the external walls are thick enough and well-insulated [15]. Soil is a heavy material and elements made from soil have high thermal conductivity (0.33-1 $W.m^{-1}.K^{-1}$), [1, 2, 3, 9, 14]. Additives such as straw, hemp and fibre can decrease this value, Steve et al. found 0,18 $W.m^{-1}.K^{-1}$by adding 25% hemp in COB walls. They also found that, the thermal conductivity of stabilized rammed earth increase with an increase in dry-density [7]. In cold region, a temperature test on adobe dwelling by Soebarto shows that, uninsulated houses cannot guarantee the desired comfort and based on his survey the ambient air temperature in the surveyed houses were between 8-12.5 °C [13]. There are researchers who has improved the thermal performance of rammed earth walls by passive design strategy such as glazing, shading and ventilation that has a positive effect on building energy consumption, however the weak thermal insulation of rammed earth (RE) is still an issue, [15, 16]. Without insulation, it is difficult to achieve U-value in earthen walls that compromises with the existing codes and regulations.

To sum up this review, the heat storage capacity of earthen elements is well studied, however the disadvantages in term of insulation is denied. Moreover, from the studied papers it was found that there is few papers that reviewed the relation between thermal mass and thermal property of RE. A very recent study on optimization of the thermal performance of composite RE walls construction proposes a comprehensive evaluation index method. They proposed design strategy for Beijing cold climate in China, and developed a quantitative design strategy for the wall thickness suitable for Beijing city [15, 16]. This research will use the same method to optimize structural layer of compressed earth block (CEB) and develop quantitative design strategy for wall thicknesses of various layer suitable for Kabul area. The authors hope that this research will provide an applicable design strategy for both CEB and RE construction in cold climate zones.

2. Research methodology

To balance the thermal performance and energy efficiency of CEB wall and establish a comprehensive evaluation index of the thermal mass and insulation: first, soil texture, density, specific heat capacity, thermal conductivity and thermal storage coefficient are evaluated. Then four relevant metrics: heat transfer coefficient, thermal inertia index, temperature wave attenuation and phase detection time were chosen. With the help of Archiwizard and WUFI pro software, the connections between those relevant were analysed and a comprehensive multi-index evaluation method was established. Finally, appropriate thicknesses for new CEB wall were derived.
For this study, Kabul was selected as a typical cold city in the cold region of Afghanistan. Kabul has a semi-arid climate with hot summer and cold winter (Fig. 1).

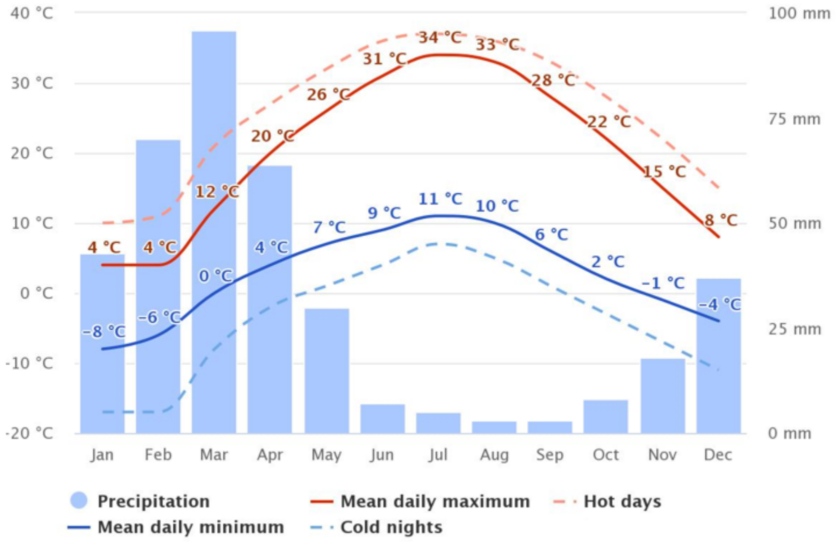

FIGURE 1. 30-year average temperature and precipitation for Kabul city, [10]

3. Material and CEB properties

Raw soil taken from Kabul city with a dry apparent density (1594 kg/m^3) was wet-sieved and analysed, according to ASTM [4], and its particle size distribution was determined (Table. 1). The result shows, it is a silty clayed soil.

TABLE 1. Raw soil particle size distribution

Soil particle size	**clay**	**Silt**	**Sand**
Distribution (%)	27,6	70,4	2

Compressed Earth Blocks measuring (290 x 145 x 100) mm using a manual hand-operated constant volume block machine were produced. All necessary physical properties of the block were determined, and the ISOMET Model 2104, heat transfer analyser, was used to evaluate the thermal performance of the blocks (Table. 2).

TABLE 2. Physical parameters of the block

Name	**Dry density ρ (kg/m^3)**	**Specific heat capacity c (kJ.kg^{-1}.K^{-1})**	**Thermal conductivity λ (W.m^{-1}.K^{-1})**	**Thermal storage conductivity S (W.m^{-2}.K^{-1})**
CEB	1860	0,844	0,728	9,116

4. Building prototype

To optimize the CEB wall thickness, an energy consumption model was established and the impact of different wall thickness on building energy demand were analysed. The energy demand analysed only for heating of the house during cold period. The east wall of the model house was considered as a shared wall with the neighbour and has zero energy lost. It is a single story one bedroom, one living room with kitchen and bathroom (Fig. 2 and Fig 3). The specification of the base case model summarized in Table. 3.

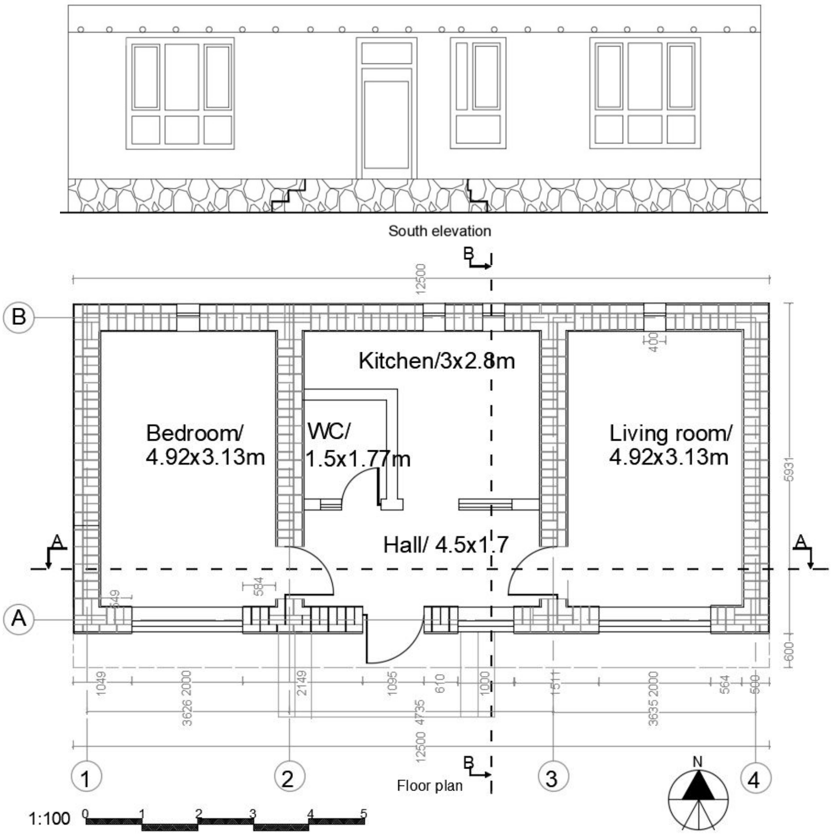

FIGURE 2. Prototype model, plan and elevation

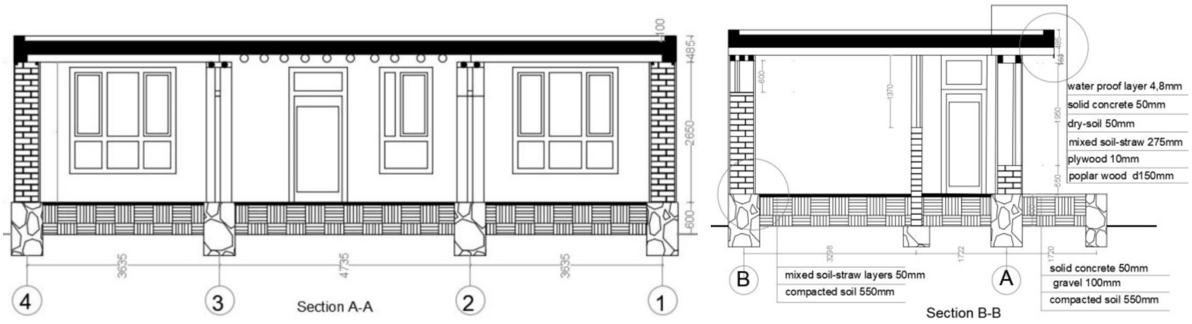

FIGURE 3. Prototype model, cross sections

TABLE 3. Specification of the base case model

Prototype residential house model

Window to wall ratio (%)	South: 27,0 North: 2,8 East: 0,0 West: 0,0
Wall U-value (W/(m².K))	Varies with wall thickness
Roof U-value (W/(m².K))	0.728
Floor U-value (W/(m².K))	0.492
Window U-value (W/(m².K)))	1.598
Heating set point (°C)	19
Ventilation	Air ventilation

5. Sub-factors

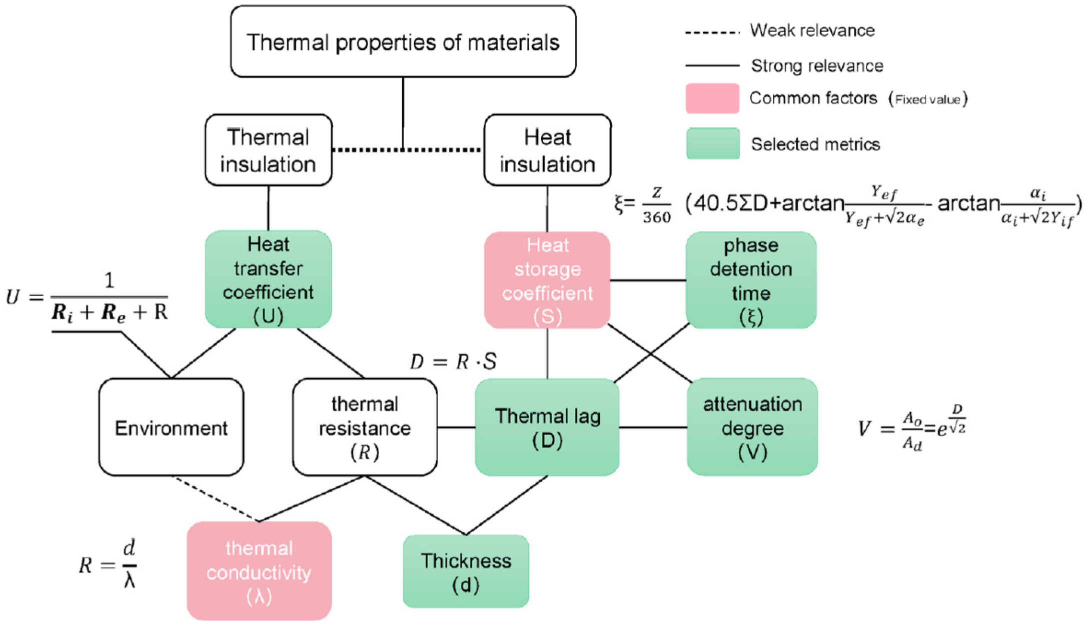

FIGURE 4. Relevance of the material's thermal parameters [15]

For evaluating the thermal performance of the CEB wall, two factors are commonly used: the thermal conductivity and heat storage capacity. The temperature, indoors and outdoors, and the constant state of wall heat transfer have great effect on the thermal conductivity; the greater the thermal conductivity of the wall the more heat loss that occurs. However, the thermal storage capacity is the heat transfer caused by the outdoor environment. Fortunately, CEB has a good thermal storage capacity and the ability to absorb, store and release heat. Yu et al. (2022) have converted the two factors into more detailed parameters (Fig. 4), and showed the relationship (weak or strong) between these parameters and their influence on RE building performance [15]. However, in this study, the same factors and parameters are used to analyse the thermal insulation and thermal mass that affect the CEB building performance, considering the physical properties of CEB and the outside climate impact. Using the wall thickness as the only variable, a comprehensive evaluation index has been established following these parameters: heat transfer coefficient, thermal inertia index, attenuation degree and phase detention time to evaluate the thermal performance of the CEB walls.

6. Analysis and calculations

As a general fact, when the wall thickness increases, the thermal insulation and thermal mass increase. However, it is not logical to blindly increase wall thickness in order to improve its insulation properties because this act decreases the usable space and makes the building vulnerable to seismic risk as CEB is a heavy weighted material. In this research, ArchiWIZARD was used to simulate energy demand of the house, and WUFI Pro was used to dynamically analyse the heat and moisture transfer. Then the parameters (heat transfer coefficient, thermal inertia index, attenuation degree and phase detention time) were fitted to the varying wall thicknesses to analyse the optimum effective thickness of the CEB walls.

6.1. Thickness and heat transfer coefficient

The WUFI Pro software was used to simulate the heat transfer coefficient of various thicknesses in the CEB walls, based on the Kabul's regional climatic parameter. The heat transfer coefficient and thermal resistance of the walls were calculated (Table. 4). The thermal resistance was calculated using the $R=d/\lambda$ formula. The internal surface heat transfer resistance ($R_i=0.125$), and the external surface heat transfer resistance ($R_e=0.0588$) were proposed by WUFI Pro. Therefore, the calculation was based on equation 1 [15].

$$U=1/(R+R_i+R_e) \qquad (1)$$

TABLE 4. Relationship between thickness and heat transfer coefficient

d mm	100	200	300	400	500	600	700	800	900	1000
U ($W.m^{-1}.K^{-1}$)	2,826	1,946	1,462	1,185	0,986	0,851	0,744	0,664	0,597	0,545
1/U ($m .K .W^{-1}$)	0,353	0,513	0,683	0,843	1,013	1,173	1,343	1,503	1,673	1,833

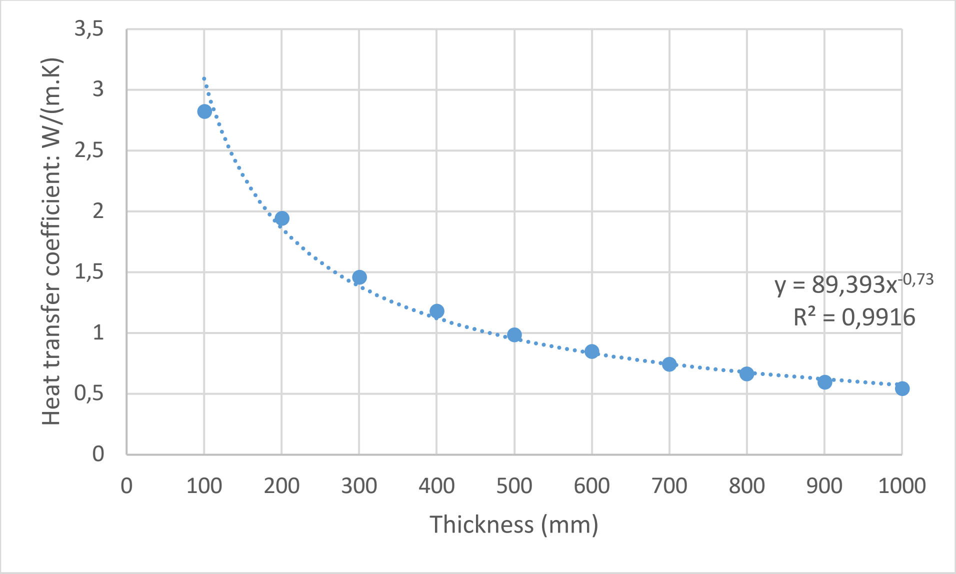

FIGURE 5. Fitting of the heat transfer coefficient

The analyse shows that with the increase in thickness, the heat transfer coefficient decreases, and the insulation performance of the CEB wall improves. Based on the above regression analyses and fitting the heat transfer coefficient to the wall thickness (Fig. 5), U= 89.4 d$^{-0.73}$ was obtained and the influencing factor of the heat transfer coefficient in the comprehensive evaluation index is a_1=0.73. The linear relationship after the dimensionless treatment of the thermal resistance is β_1=0.0016, (Fig. 6).

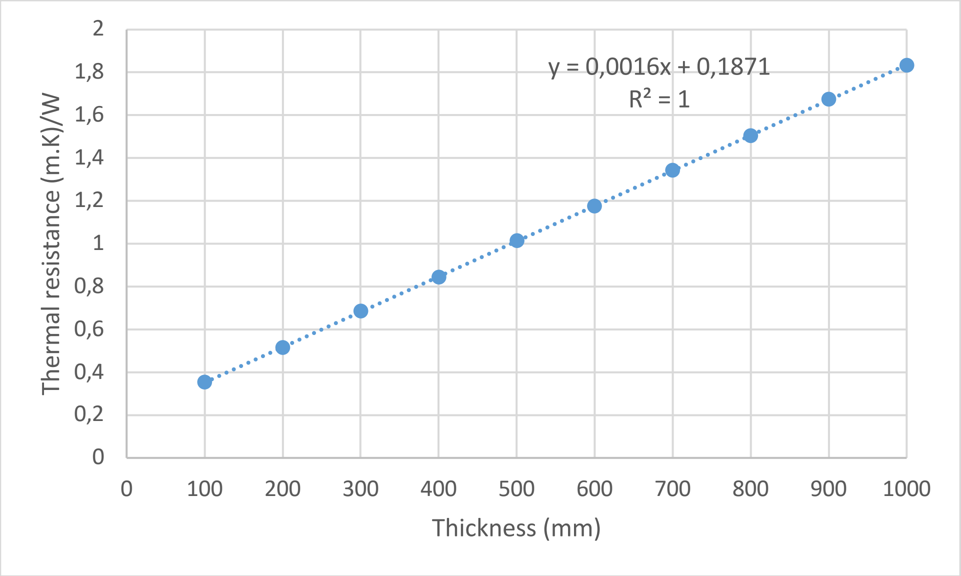

FIGURE 6. Fitting of the thermal resistance

6.2. Thickness and heat storage coefficient

The material heat storage coefficient depends on the specific heat capacity (c), density (ρ) and thermal conductivity (λ). 2π is a constant factor, and Z considered 24 hrs (86400 seconds) for equation 2 [15].

$$S = \sqrt{\frac{2\pi c\rho\lambda}{Z}} \qquad (2)$$

Since the effect of the wall thickness on the thermal storage performance cannot be accurately defined by only S, therefore, indicators related to the thermal performance of walls were taken into account to assist the measurements in this thesis. The most direct related indicator to the thermal storage coefficient is thermal inertia, and with increase in wall thickness, it becomes larger. Moreover, temperature wave attenuation degree and phase detention time establishes a direct relationship with wall thickness. By contrast, the two indirectly related indicators are attenuation degree and delay time. Moreover, the greater the thermal inertia of the wall, the better the performances of the indirect indicators.

6.3. Thickness and thermal inertia index (D)

D is a dimensionless index that reflects the decline rate of fluctuating heat transfer process of the external wall. The greater the D value is, the quicker the wall surface temperature is, and the better thermal stability of the wall. The thermal inertia index of CEB wall is equal to the heat storage coefficient multiply by the thermal resistance, equation 3 [15].

$$D = RS \qquad (3)$$

The thermal inertia index of CEB walls with different thicknesses was calculated, and the fitting function is shown in Fig. 7. It was found from the correlation of the function that the thermal inertia index of the walls is directly proportional to wall thickness, and the influence factor in the comprehensive evaluation index is a_2=1 (Fig.7) and the linear relationship β_2=0.015 (Fig.7).

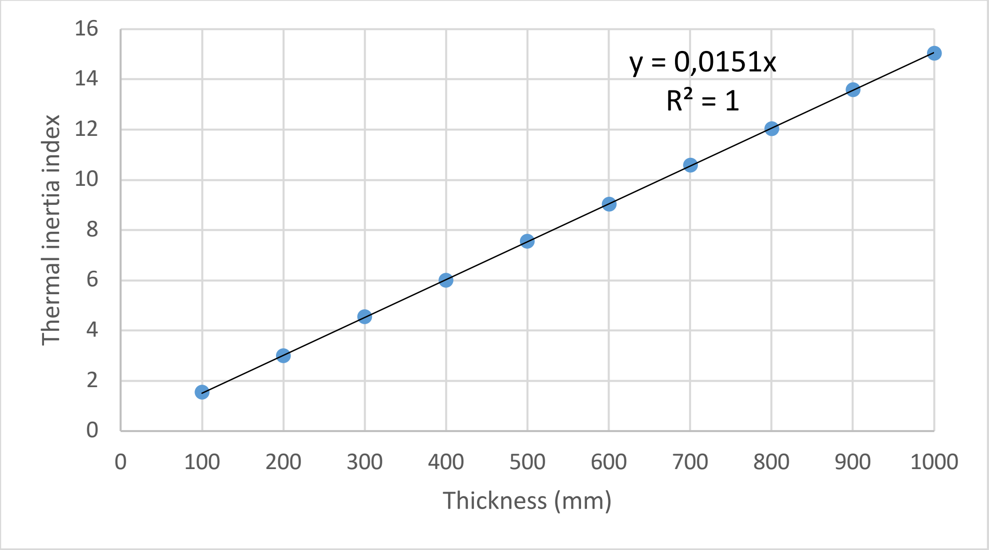

FIGURE 7. Thickness and thermal inertia index

6.4. Thickness and attenuation degree

The WUFI Pro was used to simulate the heat and moisture transfer process of the CEB walls with different thicknesses. The outside climate condition set by the software were taken from certain weather file (Kabul-hour.epw, Meteotest Ag, Bern, Switzerland) and the interior ambient temperature derived from the outside; however, the heating set-point was manually set to 19 °C. The annual variation range of the internal and external surface temperature of the walls (100-1000 mm) thicknesses was obtained by WUFI Pro simulation (Table. 5). The ratio of the harmonic amplitudes of the internal and external surface temperatures was used to measure the attenuation effect of the CEB walls on the temperature wave. The value was defined as the average annual attenuation of the temperature wave (V_0), equation 4 [15].

$$V_0= A_0/A_d \qquad (4)$$

Where A_0 is the annual temperature amplitude of the external surface of the walls, A_d is the annual temperature amplitude of the internal surface of the wall (Table. 5).

TABLE 5. Thickness and attenuation degree

d mm	**100**	**200**	**300**	**400**	**500**	**600**	**700**	**800**	**900**	**1000**
A_0 °c	42,7	43,3	43,7	43,9	44,1	44,2	44,3	44,3	44,4	44,5
A_d °c	24,4	19,2	16,9	15,7	15	14,5	14,1	13,8	13,6	13,4
V_0	1,75	2,25	2,58	2,79	2,94	3,04	3,14	3,21	3,26	3,32

With increase in thickness, the wall exterior surface temperature increased weakly, and the interior temperature decreased. Therefore, it confirms that it is logical to keep this variation, rather than using one constant degree for the exterior surface, as it is the case for two previous studies [15, 16]. Accordingly, these values were fitted with the wall thicknesses, and the results are shown in Fig. 8. As the wall thickness increased, the attenuation degree increased, and the indoor temperature fluctuation and environment fluctuation range inside the wall became smaller. However, the growing trend of A_0 became smaller, and the increase in wall thickness reaching saturation for the attenuation gain. Based on the fitting function, the influence factor for V_0 is a_3=0.272 and the correlation coefficient between attenuation and wall thickness is R^2=0.974.

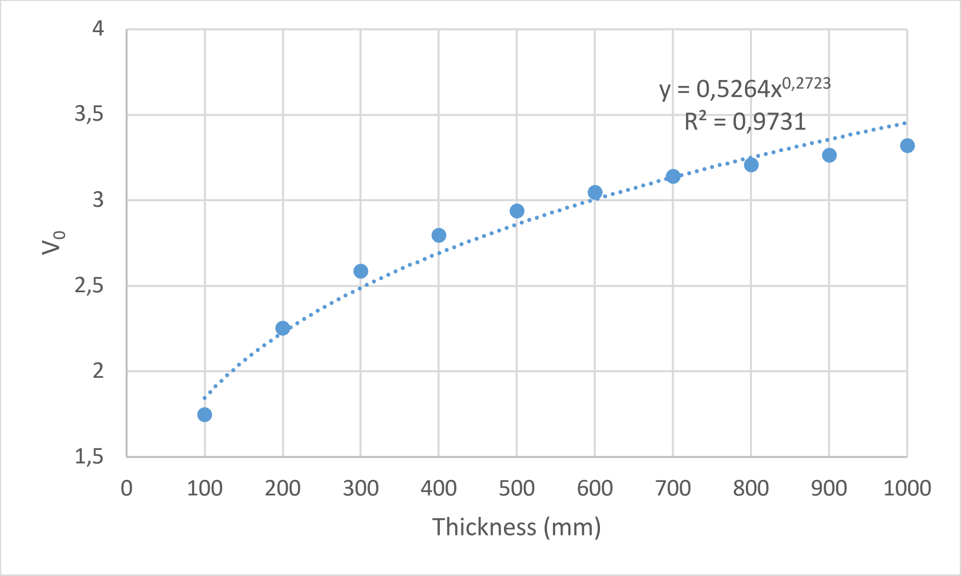

FIGURE 8. Fitting of the average annual attenuation of the temperature wave V_0

6.5. Thickness and time lag

The interval between the appearance of the peak outdoor temperature wave and the appearance of the peak indoor temperature of the exterior wall relates to the time lag (ξ). The greater the time lag, the less the impact of the outdoor temperature on building's interior environment. The delay time for the various thickness CEB walls is calculated using equation 5 [15].

$$\xi = \frac{Z}{360}(40.5\sum D \ + \arctan\frac{Y_{ef}}{Y_{ef}+\sqrt{2x_e}} - \arctan\frac{x_i}{x_i+\sqrt{2Y_{if}}} \qquad (5)$$

Where Z is the time cycle, taking the value of 24 hrs, D is the thermal inertia index of CEB; Y_{ef} is the heat storage coefficient of the external surface of the wall (W.m^{-2}.K^{-1}); x_e is the heat transfer coefficient of the external surface of the wall (W.m^{-2}.K^{-1}); Y_{if} is the heat storage coefficient of the internal surface of the wall (W.m^{-2}.K^{-1}). The power fit was performed (Fig. 9). The calculation period is for 24 hrs, and when the delay period was greater than 24 hrs, it did not make sense to continue increasing the delay time for building the indoor environmental stability. The influence factor of the delay time in the comprehensive evaluation index calculated as a_4=1 and linear relation β_4=0.04 (Fig.9).

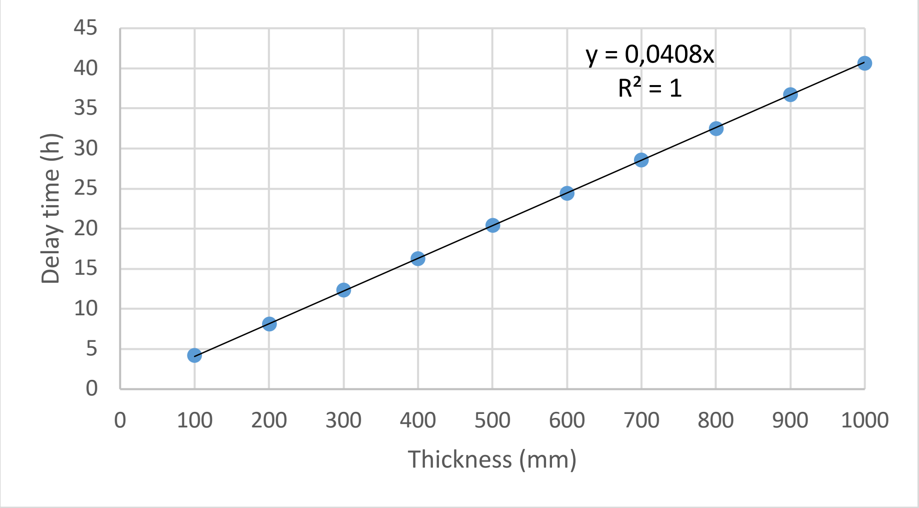

FIGURE 9. Linear fitting of the time lag

6.6. Thickness and comprehensive evaluation index

Based on the mentioned four-parameter influence factors fitted above, the comprehensive evaluation factor (M) was established using Equation 6 [15]. This factor was calculated for each wall thickness (Fig. 10).

$$M = a_1\beta_1\frac{1}{U} + a_2\beta_2 D + a_3 V_0 + a_4\beta_4\xi \qquad (6)$$

Where a_1, a_2, a_3 and a_4 are the influence factors of the four parameters and β_1, β_2, and β_4 are the linear relationship after dimensionless treatment of each parameter.
The results show, as the wall thickness increased, the comprehensive evaluation index continued to increase.

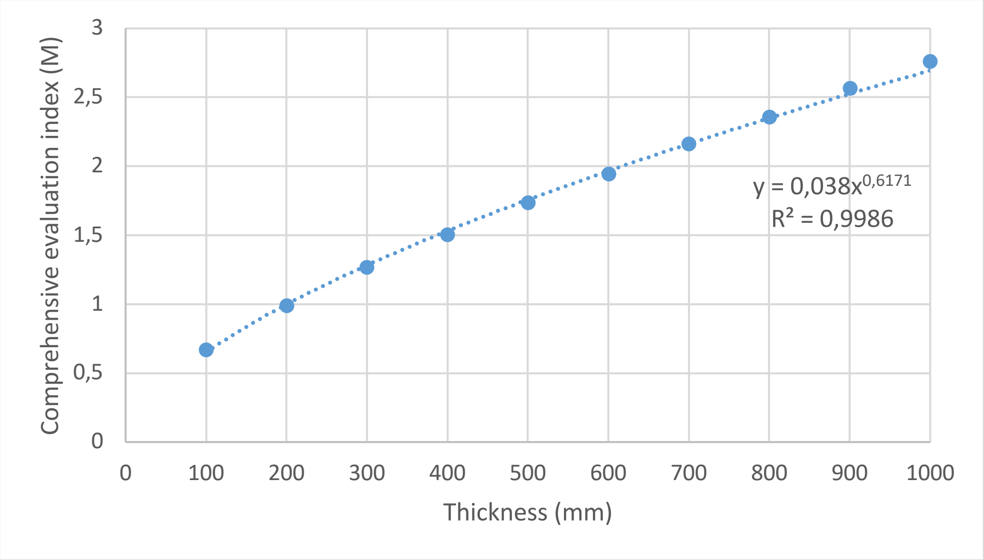

FIGURE 10. The relation between thickness and M

6.7. Building energy demand

The thermal performance of the CEB walls could be conceived by the energy demand of the building. The energy demand calculated only for heating the house where in Kabul city counts for 91% of energy usage. Therefore, the CEB walls thickness as the only variable was used to study the building energy demand under various conditions. The effect of CEB walls thicknesses (100-1000) mm on the energy demand was simulated using ArchiWIZARD GRAITEC software (Fig. 11). To find the relation between the energy saving rates and the thermal performance, two parameters were introduced. These are the energy consumption data (Fig. 11), which were processed to achieve the energy saving rate for the walls (n_e), and the comprehensive evaluation index data (Fig. 10), which was processed to find the thermal performance improvement rate (n_M); they were calculated suing Equations 7 and 8 [15]. The intersection between the two factors specified the optimum CEB wall thickness (Fig. 11).

$$n_e = (E_n - E_{n+1}) / E_n \qquad (7)$$

$$n_M = (M_n - M_1) / M_1 \qquad (8)$$

Where E_n and E_{n+1} are the building energy consumption before and after gradient change, respectively; M_n is the composite index after the performance improvement; and M_1 is the initial composite index. When $n_e > n_M$, the thermal performance improvement gain had a positive meaning; however, when $n_e < n_M$, the thermal performance improvement gain declined and had a negative meaning; further, when $n_e = n_M$, the thermal performance gain was at a maximum.

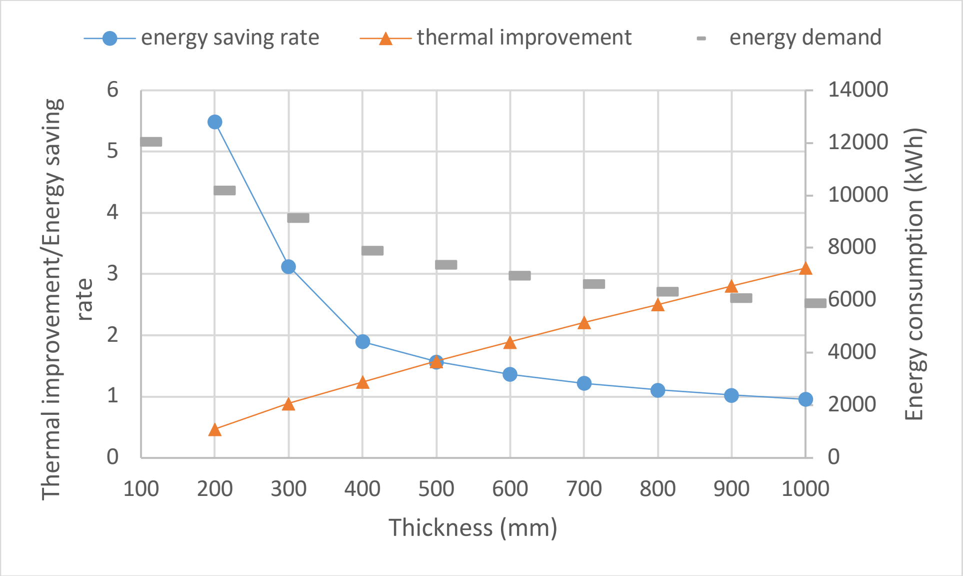

FIGURE 11. Energy saving rate, thermal improvement, and energy demand for CEB walls

Performing the same procedure and analysis [15], the following results were achieved and conclusions drawn:

1. Energy saving rate and energy consumption gradually decreased with improvement in thermal performance of the wall.
2. The energy saving rate and performance improvement reached a balance when the wall thickness reached 500 mm, achieving its best performance.
3. Considering the lower limits of the wall thickness, an optimization was found, and the appropriate CEB wall thickness for Kabul is around 500 mm.
4. Considering this thickness, the proposed wall thickness consists of 1,5 CEB (445 mm), 10 mm of joint mortar, and 30 mm soil-straw plaster on both sides of the wall, and the total wall thickness reached 505 mm.
5. The 30 mm of soil-straw plaster with lower thermal conductivity improved heat the transmittance of the wall from 0,981 $W.m^{-2}.K^{-1}$ to 0,859 $W.m^{-2}.K^{-1}$. This also reduced the annual energy demand of the building from 7894 kWh for 500 mm CEB wall to 6377 kWh for 505 mm composite wall. In addition, the plaster is able to protect the wall from rain and environmental impact.

7. Conclusion

The purpose of this research was to optimize design strategy for affordable housing program in Kabul city. A mathematical model with CEB walls was used to study the influence of the thermal performance on the indoor environment. Four parameters: heat transfer coefficient, thermal inertia index, attenuation degree and phase detention time that affect the thermal performance of the model house were numerically studied and a comprehensive evaluation index was established. The analyse suggested, the optimum CEB wall thickness for Kabul is around 500 mm, and when this thickness exceeds this value, the thermal performance gradually declined. To protect the CEB wall from rain and environmental impact, 60 mm soil straw plaster was added on the exterior and the interior wall surfaces. The plaster had improved the U-value of the wall and decreased the energy demand of the model house, relatively.

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