Evaluation of structural performance and energy saving ability of normal, voided and foamed RC slabs

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ABSTRACT
Saving energy consumed in buildings has become an important factor in design. Thus, the aim of this research is to assess the thermal and structural performance of different types of concrete slabs using real simulation for heat transferred from solar radiation, and from difference between indoor and outdoor temperatures in the existence of dead and imposed loads. Three types of slabs were examined: normal, voided and foamed concrete. Moreover, the effect of slab end conditions was investigated. Thermal analysis was performed for each slab type considering summer and winter weather of Egypt. In this analysis, the heat transferred through each slab was calculated, and hence the ability of each type to maintain the indoor temperature could be determined. The non-uniform distribution of temperature along the thickness of each slab type was used through structural analysis to examine the performance of the considered slabs under the effect of thermal actions and static loads. Both voided and foamed concrete slabs maintained successfully the indoor temperature from being affected by the climatic conditions; whereas, the best from a structural point of view was in favor of voided slabs as clarified through this research.

ARTICLE HISTORY Received 29 March 2019; Accepted 20 May 2019

KEYWORDS Heat transfer; thermal analysis; structural analysis; normal concrete slab; voided slab; foamed concrete slab; energy conservation

Introduction
Energy conservation has become an important target when designing buildings due to increasing public awareness and actions taken by governments in many countries around the world to mitigate energy crises. It was found that building sector consumes one third of the final energy use [1]. One of
the main reasons of this is the dependency on air conditioning system [2]. These devices not only considered energy consuming devices but it also contributes in environmental problems and global climate change. Thus, saving energy demand of the buildings became an important condition for any policy of climate change [3]. The energy efficiency, which means the capability of consuming less energy, can be achieved by choosing suitable materials and structural systems for a building envelop to protect the indoor environment from the changes of external weather. This could save energy consumed for cooling or heating and at the same time assure human comfort.

Roof slab is part of building envelop that is subjected daily to significant amount of solar radiation and variations in outdoor temperature and air velocity, which increase the heat transferred to indoor environment and the dependency on air conditioning system to keep suitable temperature. By using these devices, the roof slab is subjected to large difference between indoor and outdoor temperature especially in summer in hot countries, which may lead to larger deformations and higher cracks occurrence [4–6]. Therefore, according to most of the current codes and standards such as [7–9] the structural elements shall be checked under thermal actions to ensure that the additional thermal deformations don’t cause overstressing to these elements. Therefore, many researchers were interested in studying traditional normal concrete slabs under the influence of real climatic conditions whether experimentally or by making real simulation for heat transfer using numerical or analytical methods [6,10–12]. However, the main issue is to find new alternative to increase the energy efficiency of roof slab, whether by using material with low thermal conductivity such as foamed concrete or by using structural system that can separate between outdoor and indoor environment, such as voided slabs. Foamed concrete is a lightweight concrete where low density is achieved by increasing the volume of air pores by introducing the performed foam in the concrete mixture that also contains water, fine aggregates and hydraulic cement, which may contain supplementary materials, such as fly ash. This mixture reduces the thermal conductivity of concrete leading to good thermal insulation and fire resistance, in addition to the feature of weight reduction [13–17]. In voided slabs, the weight is reduced by providing voids at the middle of the thickness of the slab, where there is no significant stress. There are several types of voided slabs starting from traditional precast hollow core slab to the cast-in-situ, bubble-voided and tube-voided slabs [18–20]. Most of the previous researches examined the structural performance and fire resistant of the voided slab [21,22], but they didn’t examine its thermal isolation capability. Thus this paper was interested in making a comparative study among the later three types of concrete slabs to assess their thermal and structural performance and find out the optimal type to be used for roofs of buildings.
Therefore, thermal and structural analyses were conducted in this research. In thermal analysis, the solar radiation and convection heat transfer from surrounding air in addition to the conduction heat transfer through each slab type were calculated to find out the temperature gradient in each type and consequently determine the heat loss through each slab. The slabs were studied under the effect of climate in Egypt throughout the 24-hours in the hottest and coldest days in the year. After that, the obtained non-uniform temperature distribution through thickness of each slab type in the existence of dead and imposed loads were used to examine the structural performance of the considered slabs. The structural performance was examined regarding natural frequencies, deflections and stresses and the results were obtained for the 24-hours for the hottest day in summer and the coldest day in winter. The effect of slab end conditions under thermal loads was also examined in this research.

**Thermal analysis for RC slabs**

Heat is transferred through the layers of the slab by three ways: convection, conduction and radiation. Convection heat transfer occurs between the slab and the surrounding moving air, while conduction heat transfer represents heat flow through the slab layers. Radiation heat transfer is quite different from the latter two methods, where it is the electromagnetic waves that is emitted by anybody have temperature greater than zero and it does not need a medium to transfer. These three mechanisms of heat transfer can be summarized in Equation 1, which considers two types of environmental conditions that affect roof slab, the temperature of the surrounding air and the solar radiation. In this equation, one-dimensional heat transfer was considered where the heat flow direction that affect the performance of the slabs is their thickness (Y-direction in this study) and this is agreed with EN ISO 13370 [23]; BS EN 1991-1-5: 2003 [7]. The full terms of Equation 1 were applied to the top surface of the slab while the convection and conduction terms only were applied to bottom surface of the slab as depicted in Equation 2.

\[
-k \frac{\Delta T}{\Delta y} = h_{ct}(T_{st} - T_o) - \alpha l \quad (1)
\]

\[
-k \frac{\Delta T}{\Delta y} = h_{cb}(T_{sb} - T_i) \quad (2)
\]

Where \( k \) is thermal conductivity of concrete, \( \Delta T/\Delta y \) is the gradient of temperature in the direction of heat flow, \( h_{ct} \) and \( h_{cb} \) are the convective heat transfer coefficients for the top and bottom surfaces, respectively. \( T_{st} \) and \( T_{sb} \) are the top and bottom surfaces temperature of the slab,
respectively. $T_o$ and $T_i$ are the outdoor and indoor temperature, respectively; $\alpha$ is absorptivity of concrete slab and $I$ is the total solar irradiance. The convection heat transfer coefficients are calculated according to ASHRAE 2013 [24] by using the following equations:

$$h_c = \frac{Nu \times k_a}{L_c}$$

(3)

Where $k_a$ and $L_c$ are air conductivity and characteristic length of the slab, respectively. $Nu$ is the Nusselt number which is calculated according to the type of convection forced or natural convection. For the top surface, the Nusselt number was calculated based on forced convection, Equation 4, where the air surrounding the top surface is forced with wind.

$$Nu = \begin{cases} 
0.664 R_e^{1/4} P_r^{1/4} & R_e < 5 \times 10^5 \\
0.037 R_e^{1/4} P_r^{1/4} & R_e > 5 \times 10^5 \\
(0.037 R_e^{1/4} - 871) P_r^{1/4} & R_e = 5 \times 10^5 
\end{cases}$$

(4)

Where, $R_e$ and $P_r$ are the Reynolds number and Prandl number, respectively, and can be calculated using the following equations:

$$R_e = \frac{V L_c}{\nu}$$

(5)

$$P_r = \frac{c_p \mu}{k_a}$$

(6)

Where, $V$ is wind speed, and $\nu$ is air kinematic viscosity. $c_p$ and $\mu$ are air specific heat and air dynamic viscosity. On the other hand, the convection between the bottom surface of the slab and the air of indoor temperature is considered natural convection where the motion of the air occurs due to the difference in temperature only. Thus the Nusselt number was calculated based on Equations 7 and 8 for downward and upward heat flow, respectively.

$$Nu = \begin{cases} 
0.54 R_a^{1/4} & 2.2 \times 10^4 < R_a < 8 \times 10^6 \\
0.15 R_a^{1/4} & 8 \times 10^6 < R_a < 1.5 \times 10^9 
\end{cases}$$

$$Nu = 0.27 R_a^{1/3}$$

(7)

(8)

Where $R_a$ is the Rayleigh number and was calculated based in the following equation

$$R_a = \frac{g \beta \rho^2 |\Delta| L_c^3 P_r}{\mu^2}$$

(9)
Where $g$, $\beta$, $\mu$ and $\rho$ are gravitational acceleration, coefficient of thermal expansion, air dynamic viscosity and air density, respectively. $L_c$ is the characteristic length for natural convection of horizontal surface and it equals to area of slab divided by its perimeter, while, $|\Delta t|$ is the difference between surface temperature and air temperature. Thus by solving Equations 1 and 2 numerically with the knowledge of climate conditions, and solar irradiance at any time, the temperature of the top and bottom surface of the slab were obtained. To find out the gradient of temperature through slab thickness, a thermal analysis was utilized using the obtained surface temperatures from numerical solution which was set as boundary conditions for a 3D thermal model constructed in ANSYS software [25] as will be explained.

**Thermal model and validation**

A heat conductivity model was constructed using ANSYS program [25], in which the concrete was modeled by thermal element solid 90. It is a 20 node element with single degree of freedom, temperature, at each node. The steel reinforcement was modeled using link180. It is a uniaxial element with the ability to conduct heat between its nodes. The efficiency of the proposed thermal analysis and the chosen elements for thermal model was checked through a validation study on a concrete slab constructed on Shenzhen, China and tested experimentally by Xia et al. [6]. The temperature at each 20 mm along the slab thickness was recorded using embedded thermocouples for 24-hour on 11 February 2009. The area of the slab was $3200 \times 800$ mm$^2$ with thickness 120 mm as shown in Figure 1(a). The slab was simply supported with overhang 100 mm at each end. The concrete was C30 and the steel reinforcement was Ø12 mm every 150 mm in the main direction and Ø 10 mm every 200 mm in the other direction with a

**Figure 1.** (a) Experimental RC slab (Xia et al. 2011). (b) Temperatures gradient through the slab for 24-hours (Xia et al. 2011) [6]. (c) Temperatures gradient from Finite element analysis.
cover thickness of 15 mm. The concrete slab was divided into elements with length 50 mm in \( X \) and \( Z \)-directions. While it was divided to 20 mm thick elements in \( Y \)-direction to maintain the desired aspect ratio for the analysis. The material thermal properties were considered as mentioned by Xia et al. [6]. The thermal conductivity of the slab was 1.74 W/m°C, the specific heat was 920 J/kg°C and the absorptivity coefficient was 0.7. The solar irradiance and the ambient temperature at different times during the day were considered as mentioned by Xia et al. [6]. The top and bottom surfaces temperature were calculated numerically then they were used as boundary conditions for heat conductivity model in ANSYS program [25] to find out the temperature gradient along the thickness of the slab. The results obtained were compared with the experimental results of Xia et al. [6] as shown in Figure 1(b) and (c). Good agreement was noticed between the results proving the ability of thermal model and thermal analysis to predict thermal behavior of different RC slabs.

**Thermal performance of different RC slabs**

Different slab types with different material properties were studied using the verified elements and analysis. The slabs were considered in Egypt (latitude 30.044 and longitude 31.236). The top surfaces of the slabs were exposed to environmental temperature during the year without any insulation. The analyses were conducted under the weather of Egypt in year 2015. The weather data was obtained by the European project, SoDa pro [26] that gives an access to various web services that provide weather and solar-related data. The air temperature, pressure, wind speed and directions were obtained from the web service of the Modern-Era Retrospective Analysis for Research and Applications (MERRA) [27] that is undertaken by the National Aeronautics and Space Administration (NASA). The solar irradiance data was collected from the web services of the European Earth observation program Copernicus Atmosphere Monitoring Service (CAMS) [28]. In year 2015, the maximum temperature and minimum temperature occurred on 16 August and 2 February, respectively. Thus, the analyses were conducted for 24-hours for these two days to find out the thermal performance of roof slabs considering the hottest and coldest days through the year and the weather and solar irradiance data of these days are clarified in Table 1. The indoor temperature and indoor air speed were taken 22°C and 0.1 m/s, respectively, for air conditioned room according to ISO: 7730 (2005) [29]. Table 2 shows the average value of thermo-physical properties of air at atmospheric pressure related to the average temperature in the coldest and hottest days considered in this research and they were calculated from the data available in Incropera et al. [30].
The above weather and solar irradiance data were used to assess the thermal performance of normal, foamed and voided reinforced concrete slabs that are shown in Figure 2. This figure shows that both normal and foamed concrete slabs considered in this research were flat slabs with solid sections, while the voided slab contains regularly distributed air-filled cavities. Each cavity or void has height equals to 50% of slab thickness \( t \) and width equals to \( t \) which was chosen in accordance with ACI 318R-14 [8].

The material properties used for normal and voided slabs were taken as in the verified slab of Xia et al. [6], which represent normal strength concrete type. The material properties of the foamed concrete slab were taken according to Liu et al. [16]. It has density equals 1700 kg/m\(^3\) which is classified as structural grade concrete with thermal conductivity equals

| Hour | Outdoor temperature (°C) | Outdoor Wind speed (m/s) | Solar intensity at top surface (W/m\(^2\)) | Outdoor temperature (°C) | Outdoor Wind speed (m/s) | Solar intensity at top surface (W/m\(^2\)) |
|------|--------------------------|--------------------------|--------------------------------------------|--------------------------|--------------------------|--------------------------------------------|
| 1    | 8.576                    | 3.5637                   | 0                                          | 28.5403                  | 4.3742                   | 0                                          |
| 2    | 8.7821                   | 3.6108                   | 0                                          | 27.99                    | 4.0781                   | 0                                          |
| 3    | 8.8648                   | 3.6772                   | 0                                          | 27.708                   | 3.5375                   | 0                                          |
| 4    | 8.6963                   | 3.8278                   | 0                                          | 29.3615                  | 2.6252                   | 11.103                                     |
| 5    | 9.9842                   | 4.0125                   | 0.8418                                     | 33.3308                  | 2.0185                   | 157.6405                                  |
| 6    | 13.0824                  | 3.6913                   | 113.5527                                   | 38.1972                  | 1.82                     | 376.8793                                  |
| 7    | 16.1137                  | 3.1937                   | 330.5817                                   | 42.0371                  | 1.3145                   | 590.2788                                  |
| 8    | 17.8941                  | 3.848                    | 525.9637                                   | 44.794                   | 0.89                     | 769.4562                                  |
| 9    | 19.3926                  | 4.4874                   | 671.0789                                   | 46.4481                  | 1.0063                   | 897.5897                                  |
| 10   | 20.2716                  | 4.6299                   | 752.2405                                   | 47.1328                  | 1.478                    | 963.9156                                  |
| 11   | 20.4727                  | 4.6783                   | 762.2827                                   | 47.033                   | 2.143                    | 962.7617                                  |
| 12   | 19.974                   | 4.5768                   | 700.3047                                   | 46.1258                  | 3.0521                   | 893.8164                                  |
| 13   | 18.7885                  | 4.2128                   | 571.6433                                   | 44.3889                  | 4.3502                   | 762.4421                                  |
| 14   | 17.088                   | 3.4943                   | 388.0127                                   | 41.7981                  | 5.9047                   | 580.2998                                  |
| 15   | 15.1904                  | 3.585                    | 172.0484                                   | 38.2884                  | 7.2148                   | 365.5869                                  |
| 16   | 14.1997                  | 3.9612                   | 13.9315                                    | 34.8426                  | 7.8483                   | 148.2761                                  |
| 17   | 13.2842                  | 4.3137                   | 0                                          | 32.6088                  | 7.6234                   | 12.8214                                   |
| 18   | 12.456                   | 4.4472                   | 0                                          | 31.252                   | 6.8083                   | 0                                          |
| 19   | 11.7632                  | 4.3981                   | 0                                          | 30.2175                  | 6.0691                   | 0                                          |
| 20   | 11.0658                  | 4.325                    | 0                                          | 29.3195                  | 5.4932                   | 0                                          |
| 21   | 10.4916                  | 4.54                     | 0                                          | 28.5724                  | 5.0498                   | 0                                          |
| 22   | 10.2303                  | 4.6362                   | 0                                          | 28.0294                  | 4.7206                   | 0                                          |
| 23   | 10.1541                  | 4.3985                   | 0                                          | 27.4912                  | 4.4923                   | 0                                          |
| 24   | 10.2426                  | 4.0387                   | 0                                          | 27.1013                  | 4.2925                   | 0                                          |

**Table 1.** Solar intensity, outdoors properties in winter day and summer days.

**Table 2.** Thermo-physical properties of air at atmospheric pressure.

| Physical properties of air | Average value in winter | Average value in summer |
|----------------------------|--------------------------|-------------------------|
| Specific heat, \( c_p \) (kJ/kg C) | 1.007                    | 1.0075                  |
| Coefficient of thermal expansion, \( \beta \) (1/C) | 0.0035                   | 0.0034                  |
| Thermal conductivity, \( K_0 \) (W/m°C) | 0.0253                   | 0.027                   |
| Density, \( \rho \) (kg/m\(^3\)) | 1.22                     | 1.125                   |
| Dynamic viscosity, \( \mu \) (Ns/m\(^2\)) | 0.179 × 10\(^{-4}\) | 0.19 × 10\(^{-4}\) |
| Kinematic viscosity \( \nu \) (m\(^2\)/s) | 0.148 × 10\(^{-4}\) | 0.17 × 10\(^{-4}\) |
0.58 W/m°C and 30 MPa comprehensive strength. The absorptivity coefficient \( \alpha \) was considered 0.7 for all slabs according to BS EN 1991-1-5: 2003 [7], where it depends on the color of the surface. All slabs were 3.0 m x 3.0 m with thickness equals 0.16 m (Figure 2).

The non-uniform temperature distribution through the layers of the studied slabs during the day hours in the summer day and winter day are shown in Figure 3, where, \( T_0 \) refers to the temperature at the bottom of the slab, \( T_{20} \) refers to the temperature at the first layer (20 mm from the bottom

![Figure 2. Typical profile of investigated slabs (a) normal and foamed concrete slab, and (b) voided slab.](image)

![Figure 3. Variation of the temperatures through normal, foamed and voided concrete slabs during 24-hours in the hottest and coldest days in Egypt in 2015.](image)
of the slab), etc. This figure shows that both foamed and voided slabs could keep the interior surface of the slab near the indoor temperature while the normal concrete slab couldn't prevent the external weather effects in summer and winter. In summer at mid-day the temperature of the inner surface of the normal slab reaches 37.4°C, which will be transferred to indoor environment by radiation causing rising in indoor temperature. This means more electricity consumption by air conditioning system to reach the comfortable temperature. Another important advantage for the voided slabs is that the existence of air cavities in the middle part of the slab gives the most stable internal temperature of the bottom surface during the day hours, especially in winter, as shown in Figure 3(e) and (f). This helps in making the air conditioning devices work regularly. In foamed concrete slab, although the small thermal conductivity gave good isolation for indoor environment, it increases the temperature of the top surface and the difference between the temperature of the upper and lower surfaces of the slab. This difference reaches 41.96°C at mid-day in summer which is considered a significant thermal load on the slab that may affect its structural performance. The maximum thermal loads in the normal and voided slabs were 26.38°C and 34.51°C, respectively, at mid-day in summer. This gives an indication that it is not sufficient to judge efficiency of these slabs from thermal point of view only without considering their structural performance in the presence of this large temperature gradient.

**Structural analysis of RC slabs**

The temperature gradient obtained from thermal analysis through the thickness of the slabs was used to examine the structural performance of the three considered slabs, normal, foamed and voided concrete slabs in the existence of dead and imposed loads. The slab end conditions were investigated as well. The slabs were examined for the 24-hours of the hottest day (summer day) according to the weather in Egypt, the coldest day (winter day) and under constant temperature equal 20°C, which represents the ideal state of the material of the slabs (reference temperature). This study was interested in finding out the effect of temperature change on natural frequency and on responses of the slabs, such as deflection and stresses.

**Structural model and validation**

Three dimensional finite element models for one-bay and multi-bays slabs, as shown in Figure 4, were constructed and analyzed using ANSYS program [25]. The slabs were modeled by using concrete element (SOLID 65), which has the capability of cracking in tension and crushing in compression to represent the nonlinear behavior of concrete. This element is represented by
eight nodes with three translational degrees of freedom at each node. The steel reinforcement was modeled separately, as shown in Figure 4(b), using the spar element (LINK180). Eight-node solid element (solid185) was used to model the loading plates at positions of supports of the verified slab tested by Xia et al. [6], which is shown in Figure 1(a). All slabs studied through this research were modeled with the associated supported columns, as shown in Figure 4, to get accurate behavior for deformation and rotation under thermal and static loading. Suitable mesh size was selected for the solid elements with aspect ratio did not exceed 1:3 to obtain accurate results with reasonable time for calculation.

**Material modeling**

Two nonlinear material models were used to model the behavior of concrete and steel reinforcement, as shown in Figure 5. Bilinear stress–strain relationship was used to simulate steel reinforcement. The ultimate and yield strengths for reinforcement were 600 and 400 N/mm$^2$, respectively, while the Poisson’s ratio and the Young's modulus equal 0.3 and 210 GPa, respectively. The nonlinear curve used to represent compressive stress–strain relation of concrete is divided into three phases as illustrated in following equation.

\[
\sigma_c = \begin{cases} 
\frac{E_c \varepsilon_c}{f_{ck}} & 0 \leq \varepsilon_c \leq \frac{0.4f_{ck}}{E_c} \\
\frac{0.4f_{ck}}{E_c} \leq \varepsilon_c \leq \varepsilon_{c2} & \\
\varepsilon_{c2} \leq \varepsilon_c \leq \varepsilon_{cu} \end{cases}
\]

(10)

The concrete behaves in elastic manner until the stress reaches approximate value equal to 0.4 of the characteristic compressive strength of concrete $f_{ck}$ according to EN 1992-1-1 [31]. This is followed by a transition from elasticity to perfectly plastic behavior which starts when the stress of concrete reaches the value of $f_{ck}$ at strain $\varepsilon_{c2}$ and continue until the strain, $\varepsilon_c$, reaches its ultimate values ($\varepsilon_{cu}$), where the crushing occurs. For normal concrete material considered in this research, the characteristic comprehensive and tensile

![Figure 4.](image-url)
strength equal to 30 and 2.6 MPa, respectively, while the Poisson’s ratio $\nu$, and the Young’s modulus $E_c$ equal 0.2 and 31 GPa, respectively. The ultimate strain $\varepsilon_{cu}$ and the thermal expansion was taken as $0.0035 \times 10^{-6}$, respectively, while the density was approximately equal to 2316 kg/m$^3$ as the verified slab. For the foamed concrete which is considered light weight concrete where its density was 1700 kg/m$^3$ as illustrated before, it has the same comprehensive strength as the normal concrete, which equals 30 MPa. The other properties of light weight concrete are reduced than the corresponding values of normal concrete by a ratios related to the density as specified in EN 1992-1-1 [31]. The modulus of elasticity, the tensile strength and the ultimate strain of light weight concrete were calculated according to the following equations

$$E_{Lc} = E_c \times \eta_E$$

$$f_{Lct} = f_{ct} \times \eta_1$$

$$\varepsilon_{Lcu} = \varepsilon_{cu} \times \eta_1$$

$$\eta_E = \left(\frac{\rho}{2200}\right)^2$$

$$\eta_1 = 0.4 + 0.6 \frac{\rho}{2200}$$

Where, $\eta_E$ and $\eta_1$ are the conversion factor for calculating the modulus of elasticity and a coefficient for determining tensile strength. $\rho$ is the density of foamed concrete. The thermal expansion of foamed concrete is taken $7 \times 10^{-6}$ according to EN1991 1-5 [7]. The effect of temperature on concrete material is taken into consideration in this research according to CEP-FIP 1990 [32] where

**Figure 5.** (a) Nonlinear stress–strain relationship for concrete. (b) Bilinear stress–strain curve for reinforcement.
the modulus of elasticity and compressive strength without exchange of moisture and in the range of temperature from 0°C to 80°C can be estimated using the following equations:

\[ E_c(T) = E_{c0} \left(1.06 - \frac{0.003T}{T_0}\right) \]  

\[ f_{cm}(T) = f_{cm0} \left(1.06 - \frac{0.003T}{T_0}\right) \]  

\[ f_{cm} = f_{ck} + \Delta f \]  

Where \(E_c(T), E_{c0}\) are the modulus of elasticity at temperature \(T\) and at temperature 20°C, respectively. \(f_{cm}(T)\) is the compressive strength at temperature \(T\). \(f_{cm0}\) is the mean compressive strength at temperature 20°C which is used to estimate the strength of concrete under the effect of temperature and it is calculated according to Equation 18. \(\Delta f\) equals to 8 MPa, \(T\) is the temperature °C and \(T_0\) equals 1°C. Thus when modeling the slab, its thickness is divided into layers with different material properties according to the temperature of each layer.

**Validation of FE model**

The same slab tested by Xia et al. [6] and used for validation of thermal analysis is used to verify the structural model. The difference when utilizing structural analysis is that the slab was modeled using structural elements (SOLID65, LINK180 and SOLID185) and the material properties were defined as illustrated in the previous section. The experimental investigation carried by Xia et al. [6] was interested to find out the effect of temperature on modal data of the slab, such as frequencies and mode shapes. Therefore, the vibration of the slab was measured under the impact of an instrumented hammer using seven accelerometers. The modal data of the slab were extracted from the measurements by utilizing the Rational Fraction Polynomial method [33]. In this research to verify the suggested finite element model, modal analysis was performed using ANSYS software [25]. The effect of temperature on the stiffness of the slab was considered into the material properties by dividing the thickness of the slab to layers with different modulus of elasticity which was calculated according to Equation 16. The variation of the frequency versus temperatures along the hours of the day obtained from finite element were compared to the experimental results, as shown in Figure 6, where \(T_t\) and \(T_b\) are the temperatures of top and bottom surfaces of the slab, respectively. Good agreement was noticed between the results which indicate the ability of the suggested finite element model to examine the performance of different slab types under structural loads and non-uniform temperature load extracted from thermal analysis.
**Structural performance of slabs**

To examine structural performance of different types of roof slabs, modal and static analyses were performed. Modal analysis helped in getting slabs’ natural frequencies, while static analysis helped in studying slabs’ deflections and stresses. The dead load was taken into consideration in elements properties for both types of analyses. The effect of temperature gradient obtained from thermal analysis was considered in material properties for modal analysis while in static analysis the temperature effect was taken into consideration in both material properties and as non-uniform temperature distribution through the thickness of the slabs. The imposed load was considered in static analysis according to the Egyptian code for calculating loads and forces (ECP201-2012) [34] and it was applied on the mesh nodes of the top surface of the slab. The performance of the slabs was evaluated by comparing the response at reference temperature ($R_{\text{ref. temp}}$) and after applying temperature gradient in summer and winter days ($R_{\text{non-uniform. temp}}$), where the change was calculated according to the following equation

$$R_{\text{change}}\% = 100 \times \left( \frac{R_{\text{ref. temp}} - R_{\text{non-uniform temp}}}{R_{\text{ref. temp}}} \right)$$  \hspace{1cm} (19)

**Effect of slab type**

The behavior of normal, foamed and voided concrete slabs was examined under thermal and static loads. A one-bay flat slab was analyzed in this section, as shown in Figure 4(a). It was designed according to the Egyptian code for the design and implementation of concrete structures (ECP203-2006) [35]. The slabs’ dimensions were 3 m × 3 m and their thickness was

![Figure 6](image-url). Comparison between variation of the frequency versus temperatures obtained from finite element model and experimental results (Xia et al., 2011) [6].
0.16 m, with bottom reinforcement 6Ø 10/m and top reinforcement 5Ø 10/m. The slabs were supported on four corner columns to simulate the actual behavior of rotation and deflection. Each column was 0.3 m × 0.3 m with 4Ø 16 steel reinforcement. Figure 7 shows the maximum static responses of the three considered slabs relative to the corresponding values of normal concrete slab when they were subjected to the same ideal temperature equals 20°C (reference temperature). With regard to deflection, foamed and normal concrete slab gave approximately the same values of deflection although the lighter weight of foamed concrete. This was attributed to the reduction in modulus of elasticity that is depending on the weight of concrete, as illustrated in Equation 11. Whereas, voided slab gave significant reduction in deflection reached approximately 50% less than the normal concrete. This may be attributed to that the voided slab has a considerable weight reduction without any reduction in modulus of elasticity. Moreover, under the same temperature condition, the maximum stress was noticed in the normal concrete slab, while foamed slab showed a maximum stress of about 79% of the normal concrete slab, as shown in Figure 7(b). The least stresses were found in the voided slab which showed a maximum stress of about 47.37% of that of the normal concrete slab. Thus, the voided slab could reduce both deflection and stresses better than the light weight concrete.

Figure 8 shows the natural frequency of the first mode and deflection of each slab type during 24-hours of summer and winter days. The frequencies and deflections were relative to the corresponding value when each slab subjected to the reference temperature that equals 20°C. This temperature represents the mean temperature at which the material properties were calculated in most specifications and standards. It was noticed that both the natural frequency and deflection of each slab were changing continuously with changing the temperature during the day hours. The angular frequency decreased with increasing temperature and increases when the temperature of the slab become smaller than the reference temperature as it was found in the experimental investigation conducted by Xia et al. [6]. This may be due to the direct relation between the modulus of elasticity and

![Figure 7](image-url)  
**Figure 7.** Comparison between deflections and stresses of different RC slabs relative to the case of normal concrete slab under the same imposed loads and temperature (reference temperature, 20°C).
temperature that was illustrated in Equation 17. This leads to a change in the stiffness according to the value of temperature. The change in natural frequency due to the presence of heat was not significant and the maximum change reaches 0.84% throughout the day for foamed concrete slab in summer, as shown in Figure 8(c). This can be attributed to that foamed concrete was subjected to the maximum variation in temperature gradient since it has small thermal conductivity, as illustrated in thermal results. With regard to the deflection, it increased with increasing the temperature more than the reference temperature and vice versa. The deflection change occurs with noticeable values of up to about 6% over the day, which may lead to the occurrence of hair cracks with the passage of time. The maximum change in deflection considering temperature effects was noticed in normal concrete slab which was about 6.4%, as shown in Figure 9. Foamed concrete slab showed a slight reduction in deflection change due to its smaller coefficient of the thermal expansion than that of normal concrete. The maximum change in deflection was about 5.4% in voided slab. This may be due to the existence of air voids in the slab cross-section, which reduced the effect of the thermal flow in the slab thickness.

The stress values throughout the section depth of all types of slabs were plotted from the result of the ANSYS program, as shown in Figure 10. It was

Figure 8. Variation of the first natural frequency and static deflection in 24-hours in the considered summer and winter days relative to the case of reference temperature for the different RC slabs.
noticed that the stresses in the bottom surface of the slab was increased during summer due to the tensile stresses produced from expansion resulted from the increase in temperature, while in winter, the compressive stresses in the top surface of the slabs increased due to the shrinkage of the top surface at night hours. The described behavior of the aforementioned three slab types concludes that the more variation in the temperature throughout the slab layers leads to a higher structural response of the slab. This may give an indication, that although both foamed and voided concrete slab give good thermal isolation to indoor environment, they still need an external insulation to reduce the temperature of the top surface and hence give a better structural performance.

**Effect of slab boundary conditions**

The previous section concerned about one-bay slab with free edges. In this section the effect of thermal and static loads on continuous slabs will be handled. The continuity from two, three and four edges was studied using multi-bays flat slab. A full-shape three dimensional model with three bays in X-direction and

![Figure 9. Comparison between maximum deflection change in RC slabs due to temperatures in summer and winter.](image)

![Figure 10. Stress distribution over the thickness of the slabs in summer, winter and under reference temperature. (a) Normal concrete slab. (b) Foamed concrete slab. (c) Voided concrete slab.](image)
three bays in Z-direction was considered in this analysis, as shown in Figure 4(c). The dimensions of slab were 9.0 m × 9.0 m where every bay was 3.0 m × 3.0 m. Normal concrete material was utilized with thickness of 160 mm. The slab were reinforced by 5 Ø 10/m as a top reinforcement and 6 Ø 10/m as bottom reinforcement, and supported on columns with dimension 300 mm × 300 mm, with steel reinforcement of 4 Ø 16 bars. The static responses such as deflection and stress of this model were studied under dead and imposed loads with the existence of temperature. The analysis was performed considering temperature of summer day and winter day of normal concrete slab in addition to the case of constant temperature (reference temperature). Whereas, to find natural frequency for the different cases of slab continuity, each bay was studied individually by applying constraints represented continuity on two, three or four edges as the same as in the bays of large full-shape model. The results of these patterns were discussed with regard to that of the one-bay slab with free edges shown in Figure 4(a). At reference temperature, the slab frequency was increased over that of the free edges slab by about 6.6%, 22.9% and 23.8% in the 2-edges cont., 3-edges cont. and 4-edges cont., respectively, as shown in Figure 11(a). This indicates that the frequency increases as the continuity around the slab’s edges increase. Applying the non-uniform temperature on the slabs’ layers affected the frequency values during the days and all over the year, as shown in Figure 11(b), which represents the maximum change in slab frequency in summer and winter for each slab pattern. This figure shows that increasing the temperature causes a decrease in natural frequency and vice versa. However, this change in natural frequency had small values but it happens continuously throughout the day as illustrated before. The slab deflection under reference temperature were about 85.8%, 82.7% and 75.8% of that of the free edges slab in the 2-edges cont., 3-edges cont. and 4-edges cont. slabs, respectively, as shown in Figure 12(a). On the other hand, the deflection was more temperature-sensitive than the natural frequency. The maximum change reached 7.3% in the slab that surrounded in all directions, as shown in Figure 12(b). The change in deflection was reduced with reduction of number of continuous edges of the slab until it reached 6.41% in free edges slab. This may be attributed to that the more restriction to expansion due to temperature the more change in slab deflection. Increasing the number of continuous edges decreased tensile and compressive stresses of the slab under reference temperature to reach 79.2%, 67.3% and 29.4% in the 2-edges cont., 3-edges cont. and 4-edges cont. slabs, respectively, as shown in Figure 13. By applying non-uniform temperature on the slab layers, both tensile and compressive stresses of the slabs were affected, as shown in Figure 14. The change in the tensile stress was increased with increasing the continuity around the slab, while a negligible change was noticed in the free edges slab. The tensile stresses was increased in summer and reduced slightly in winter due to the decrease in the surrounding temperature in winter which causes contraction in the slab. The compressive stress in summer was
reduced when applying the non-uniform temperature. This may be due to the expansion which happens in the slab during summer. In winter, the compressive stresses slightly increased, as shown in Figure 14(b). The maximum increase in the slab compressive stress was noticed in the free edges slab, which allows shrinkage more than the other slab pattern.

Figure 11. (a) Angular frequency relative to the case of free edges slab at the same temperature conditions. (b) Change in angular frequency due to temperatures in summer and winter.

Figure 12. (a) Deflections relative to the case of free edges slab at the same temperatures conditions. (b) Change in deflection due to temperatures in summer and winter.

Figure 13. Tensile and compressive stresses relative to the case of free edges slab at the same temperatures conditions.
Conclusions

In this research, a comparative study was carried out between the normal, foamed and voided concrete slabs to evaluate their thermal and structural performance. This has helped to find out the suitable type to be used for roof slabs, which contributes in reducing heat transferred into the building and consequently the amount of energy consumed for cooling or heating. The main conclusions of this study were summarized in the following points:

- It was found that although the small thermal conductivity of foamed concrete gave good insolation for indoor environment in comparison with normal concrete, it increased the difference in temperature between the top and bottom surfaces of the slab which made considerable non-uniform temperature load on it. Whereas, voided slabs could kept its interior surfaces near the indoor temperature with smaller thermal action than the foamed concrete slabs due to the existences of air cavities between its top and bottom surfaces. Moreover, voided slab gave the most stable internal temperature of the bottom surface during the day hours, especially in winter which helps in making the air conditioning devices work regularly.

- Under the same imposed load and temperature conditions the voided slabs gave the smallest deflection and stresses which reached 50.57% and 47.37% respectively of that of the normal concrete slab due to the reduced weight. Whereas, in foamed concrete slab, the stress reduced due to its low density to be 79.8% of that of the normal concrete slab but with no significant reduction in deflection than the normal concrete due to its small modulus of elasticity.

- Under the load and non-uniform temperature distribution of each slab type, it was found that the natural frequency, deflection, and stresses were changing continuously with changing the temperature during the day hours. The noticeable values of change with

Figure 14. Change in tensile and compressive stresses due to temperatures in summer and winter.
temperature occurred in deflection where the maximum change reached 6.4% in the normal concrete slab. The foamed concrete showed a slight reduction in deflection change although it was subjected to the maximum non-uniform temperature load due to its smaller coefficient of thermal expansion than that of normal concrete. The least change in deflection due to the existence of temperature occurred in voided slab and it was about 5.31%. This may be due to the existence of air voids in the slab cross-section which reduced the effect of the thermal flow in the slab thickness.

- It was noticed that tensile stress increased slightly in summer and decreased in winter. The largest increase occurred in 4-edges continuous slabs because they are prohibited from expansion. On contrary, the compressive stress increased slightly in winter and reduced in summer. The largest increase occurs in the slabs with free edges due to shrinkage. Thus, slabs should be checked under the non-uniform temperature loads to ensure that no overstressing occurred.

**Disclosure statement**

No potential conflict of interest was reported by the authors.

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