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Properties and thermal insulation performance of light-weight concrete

Свойства и теплоизоляционные эффективности легких бетонов

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Ключевые слова: пенополистирол; топливная зола-уноса; легкий бетон; теплоизоляционные свойства; температурное поле; стеновой материал

Abstract. The building energy performance is becoming increasingly important, because of environmental restrictions and rising costs of fuel end energy. Therefore, improve the thermal insulation performance of wall covers of buildings is crucial. The present study evaluated the combined effects of two types of materials of expanded polystyrene (EPS) beads and unprocessed fly ash (FA) in Vietnam on properties of light-weight concrete (LWC). The calculation of mixture proportions of LWC is applied in accordance with the absolute volume method. Twelve different concrete mixtures with a water to bind ratio of 0.3 and superplasticizer SR 5000F to Portland cement ratio of 0.02 were used. The EPS beads and FA were partially replaced with the volume of fresh concrete and cement, respectively. The engineering properties, including workability, density, compressive strength, tensile strength, modulus of elasticity and basic physical properties were investigated in 12 patterns of tested LWC and its correlations were made. In addition, the definition of temperature distribution over the thickness of the experimental wall cover was applied by the ANSYS 18 software. According to the experimental results, there is a decrease in dry density and mechanical properties with increasing these EPS beads and FA contents in LWC. The results by ANSYS 18 are shown that at the same thickness of 250 mm, a wall with the blocks LWC brick has better insulation than the wall made of other materials such as solid clay brick, clay hollow brick and solid brick with slag concrete.

Аннотация. Энергоэффективность здания становится все более важной из-за ограничений окружающей среды и роста стоимости энергии на топливо. Поэтому важно улучшить теплоизоляционные характеристики внешних стен высотных зданий. В настоящей статье приведены результаты исследования влияния концентрации гранул вспененного полистирола, а также разработанной органо-минеральной добавки, состоящей из водоредуцирующего поликарбоксилатного суперпластификатора и топливной золя-уноса, обладающей пуццолановой активностью, на плотность, прочность, модуль упругости и теплопроводность легкого бетона (ЛБ), пригодного для изготовления материалов, предназначенных для возведения внешних стен высотных зданий. Расчёт состава лёгкобетонной смеси был выполнен с помощью метода абсолютных объёмов. Расход суперпластификатора составил 2 % от массы цемента при водо-вяжущем отношении, равном 0,3. Для расчёта температурного поля в поперечном сечении стены из разработанного легкого бетона была использована компьютерная программа ANSYS 18. В результате проведённых исследований было установлено, что стена, состоящая из легких бетонных блоков толщиной 250 мм, обладает лучшими теплоизоляционными свойствами по сравнению со стенами аналогичной толщины из полнотелого и перфорированного глиняного кирпича, а также из кирпича на основе шлакопортландцемента.

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1. Introduction

In recent years, buildings are large energy consumers in many countries in the world and energy demand is growing every day. The energy performance of a building is becoming increasingly important, because of environmental restrictions and rising costs of fuel end energy [1, 2]. The energy required in the building is mostly towards providing thermal comfort. To reduce the energy consumption in high-rise buildings, it is necessary to understand the thermal performance of the building envelope on the indoor environment. The studies [3, 4] the two parameters, which evaluate the thermal performance of walls are time lag and decrement factor. These are influenced by the external and internal surface temperatures of the enclosing structures of buildings.

In the climate of Hanoi – Vietnam in the summer, the outside temperature the building air is very high, sometimes up to 42 °C [5]. The temperature on the surface of the building's wall covers can be up to 50 °C when considering the effects of solar radiation factors [5, 6].

To ensure comfortable use in buildings, the temperature inside of the building is between 20÷25 °C, so the cover structure should ensure low heat transfer requirements

In order to reduce the transmission temperature from building outside to building's inside, some traditional methods have been introduced such as: Building solid brick wall and installing additional layer's insulation (layer of foam, insulating paint, or the use of hollow bricks, etc.) [7–11]. However, these solutions will increase labor, construction time, increase costs, etc. [12].

Many solutions have been proposed to increase the insulation of the walls [13–15]. One of those modern insulation solutions is using brick blocks from new material – light-weight concrete (LWC), which is capable of conducting low heat and withstanding the loads exerted on the walls of high-rise buildings.

Light-weight concretes have been successfully used in the buildings, thanks to its low dry density. LWC is an important material in reducing the dead-weight of concrete complying with special concrete structures of high-rise buildings [16–18]. To produce light-weight concrete, we can use several types of inorganic light-weight aggregates, like expanded clay, agropolite, or organic lightweight aggregates like expanded polystyrene (EPS) beads. When LWC base on inorganic light-weight aggregates has been widely used, LWC base on organic lightweight aggregates like EPS is now considered to be a new material in Vietnam [19, 20]. However, until now the structural LWC containing varying amounts of EPS beads is not specified in the standard in Vietnam.

The studies [21, 22] on EPS concretes have also revealed that mixtures produced using the normal vibration method will lead to a large number of EPS beads floating upward and serious concrete segregation, resulting in LWC while reducing its various engineering properties. This is due to the ultra-light EPS particles and being quite weak. It was found that the concrete is very prone to segregation and has low compressive strength. To improve the workability of the concrete mixtures containing EPS particles, a great deal of previous research [20, 23, 24] has used superplasticisers.

Some studies have reported the importance of using fly ash (FA) in concrete which can save a significant amount of energy and cost in cement manufacturing and also it can improve engineering properties of concrete by replacing with normal cement. For example, in these studies [25, 26] covers the use of EPS beads both in concrete and mortar, containing processed and unprocessed fly ash as the cementitious material. The concretes' dry densities were between 550 and 2185 kg/m^3. The EPS replacements ranged from 0 % to 100 %. These studies are indicated that the EPS concrete mixes produced with processed fly ash show lower water absorption values and better chemical resistance compared to the normal concrete.

The purpose of this research was to determine the properties and thermal insulation performance of light-weight concrete for the production of the wall cover, which contains varying amounts of EPS beads and unprocessed FA (Vietnam).

The aim of the present study included four specific objectives to:

(1) Microstructural characterizations of unprocessed Fly Ash «Vung Ang» and Silica Fume was carried out by Scanning Electron Microscope (SEM) and X-ray diffraction (XRD).

(2) Apply in accordance with the absolute volume method to calculate the concrete mixture compositions.

(3) The American and Russian standard's requirements were used to determine the fresh concrete and light-weight concrete properties.

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(4) Quantitatively describe the relationships between the various investigated light-weight concrete properties.

(5) Use the computer program ANSYS 18 to analyze the thermal insulation of the wall constructed from light-weight concrete brick blocks with walls constructed from some other materials.

2. Materials and Experimental works

2.1. Materials

1. The cement used was ordinary Portland cement (OPC) (40 Grade), manufactured at «Tam Diep» factory (Vietnam), specific weight of 3150 kg/m^3. The experimental results of physical and mechanical properties of cement are presented in Table 1 and the results of the chemical compositions are presented in Table 2. The particle size distributions details of ordinary Portland cement is shown in Figure 1.

Table 1. Mineralogical Composition, physical and mechanical properties of «Tam Diep» Portland cement.

Mineral composition (%)					Soundness Le Chatelier (mm)	Time of setting (min)		Compressive strength (MPa)			Standard consistency (%)
C_3S	C_2S	C_3A	C_4AF	Other		Initial	Final	3 days	7 days	28 days	
56.3	23.4	4.7	12.4	3.2	3.2	142	235	35.1	40.4	47.3	29.5

2. Good quality river sand was used as a fine aggregate, which produced from the quartz sand (QS) of «Lo River» (Vietnam) with the size of 0.15 ÷ 5 mm. The fineness modulus M_K = 3.1, specific gravity and dry density are 2650 kg/m^3 and 1650 kg/m^3. The particle size distributions details of fine aggregates is shown in Figure 1.

3. Unprocessed Fly Ash (FA) TPP «Vung Ang» (Vietnam) class F and Silica Fume SF-90 (SF90) (Vina Pacific). The chemical composition and physical properties of the FA TPP «Vung Ang» and silica Fume SF-90 are presented in Table 2 and their particle size distribution are presented in Figure 1.

Table 2. Chemical compositions and physical properties of Portland cement, FA TPP «Vung Ang» and Silica fume SF-90.

Chemical components (wt. %)	FA TPP «Vung Ang»	Silica Fume SF-90	Portland cement
SiO_2	54.62	91.65	20.4
Al_2O_3	24.17	2.25	4.4
Fe_2O_3	6.15	2.47	5.4
SO_3	2.81	-	3.4
K_2O	1.28	-	1.2
Na_2O	1.25	0.55	0.3
MgO	1.57	-	2.5
CaO	1.48	0.51	60.2
P_2O_5	1.63	0.03	-
LOI$^{(*)}$	5.04	2.54	2.2
Average particle size (µm)	7.18	0.243	8.365
Specific gravity (kg/m^3)	2320	2150	3150
Dry density (kg/m^3)	575	760	1200
Surface area (m^2/g)	5.35	14.45	0.365

Note: *$^{(*)}$LOI – Loss on ignition.*

4. Expanded polystyrene (EPS) beads were used as a light-weight aggregate with the size of 2 ÷ 5 mm. Its dry density is 18.1 kg/m^3 (Figure 5).

5. Superplasticizer SR 5000F «SilkRoad» (SR5000) (Korea). It is a new generation chemical additives based on polycarboxylate ethers with specific weight of 1100 kg/m^3 at 20 ± 5 °C.

6. Ordinary clean tap water (W) was used for both mixing concrete and curing of test concrete specimens.

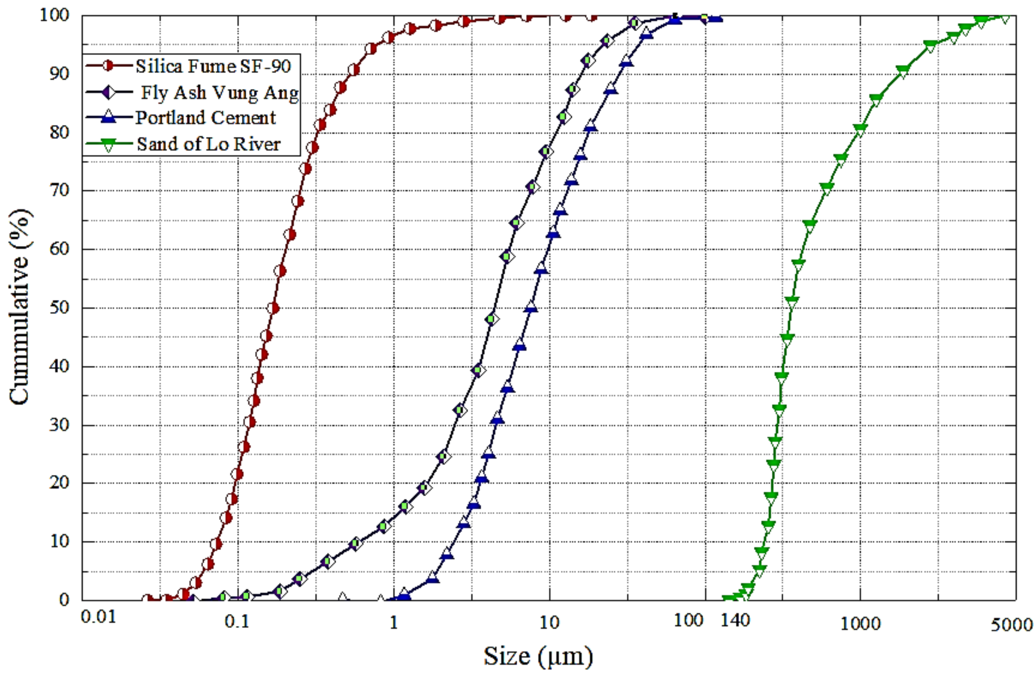
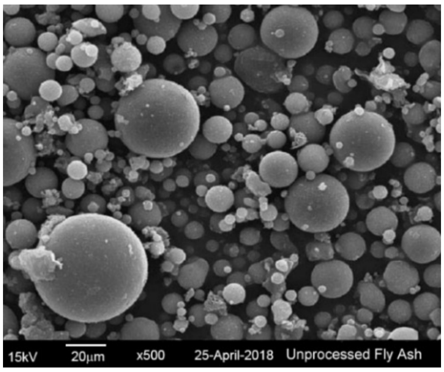


Figure 1. Sieving analysis of Silica Fume, Portland cement, Fly Ash and sand of river Lo.

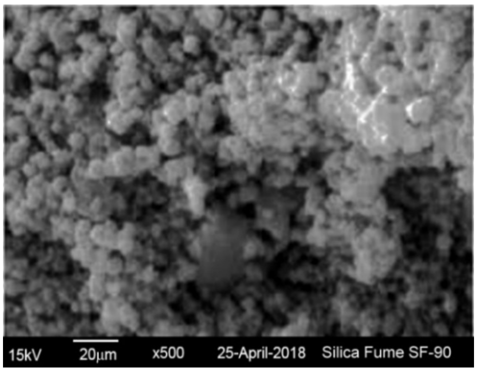
2.2. Microstructural characterizations of Silica Fume and unprocessed Fly Ash «Vung Ang»

Scanning Electron Microscopy (SEM)

The morphology of dried active mineral additives was carried out by Scanning Electron Microscope (SEM, Quanta 450, USA) operated at 15 kV. Silica Fume and unprocessed Fly Ash particles were adhered on two side adhesive black tape and kept under high vacuum to get SEM images and is shown in Figure 2. SEM images show that Fly Ash «Vung Ang» exhibit larger spherical particles, irregular in shape and found to be more porous (Figure 2a) compared with Silica Fume SF-90 (Figure 2b). The particles of Silica Fume can be seen in proper arrangement and no agglomeration occurred. The spherical particle shape of these additives can give benefit for the workability of fresh concrete at the low water-cement ratio [27].



(a)

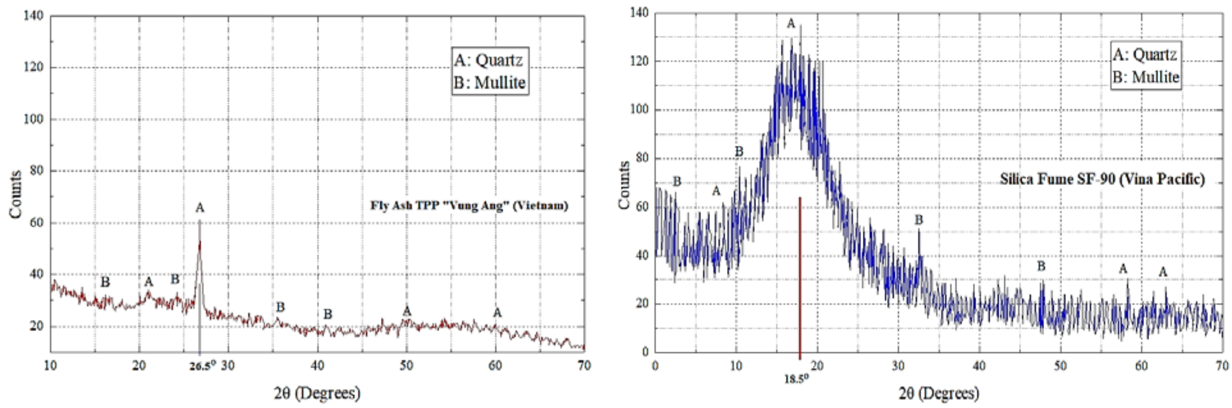


(b)

Figure 2. SEM images of (a) Unprocessed Fly Ash «Vung Ang» and (b) Silica Fume SF-90.

X-ray diffraction (XRD)

The XRD analysis provides the crystalline nature of the Unprocessed Fly Ash TPP «Vung Ang» and Silica Fume SF-90 used as the active mineral additives in mixture concrete on the device BT-9300Z. A peak with 26.5^o (2θ) was observed as the highest intensity for Fly Ash, another peak with 18.5^o (2θ) was observed as the highest intensity for Silica Fume SF-90 as are shown in Figure 3. The high peaks in both graphs corresponding to quartz silica. The rest of the peaks belonging to mineral Mullite presented in the graphs. The XRD results proved that both of the Fly Ash and Silica Fume consist of crystalline silica, which is the main important component in strength contribution. The other crystalline phase such as Mullite represent the minor phases.



(a) (b)

Figure 3. XRD analysis of (a) unprocessed fly ash «Vung Ang» and (b) Silica Fume SF-90.

2.3. Test methods

On the one hand, this paper will analyze the chemical composition and the grain composition of Unprocessed Fly Ash TPP «Vung Ang» by laser granulometry method on the device BT-9300Z. On the other hand, calculation method of compositions LWC is applied in accordance with absolute volume method. The flow ability of concrete mixture is determined by standard slump cone with dimensions of 100x200x300 mm in accordance with ASTM C143-15. Besides, the dry density of concrete is determined by standard ASTM C 138.

Compressive and Flexural Strengths of LWC specimens

The compressive strength of light-weight concrete is determined by a 70×70×70 mm cube specimen (Figure 6) by Russian standard GOST 10180-2012 at the ages of 3, 7, 14, 28 and 56 days. These cube samples are demolded after 24 hours later casting and placed in a 20 ± 5 °C water curing tank until the experiments.

The flexural strength of the LWC specimens was determined in accordance with ASTM C 78 on the 100×100×400 mm prismatic patterns and using the method of third point loading. The flexural strength of concrete was measured at 28 days.

Figure 4. Unprocessed fly ash TPP «Vung Ang».

Figure 5. Expanded polystyrene beads.

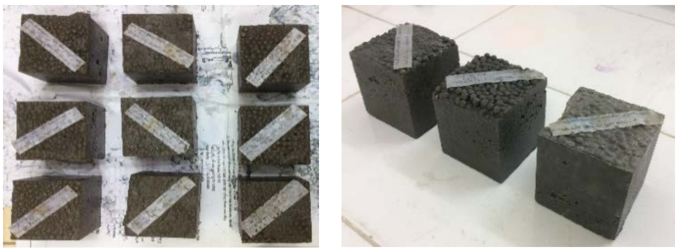


Figure 6. Specimens with the size of 70x70x70 mm of light-weight concrete.

Figure 7. Failure of concrete specimen under compression.

Modulus of elasticity

The static modulus of elasticity, which corresponds to the secant modulus, was determined for light-weight concrete in accordance with ASTM C 469-2002 at 28 days of age.

Thermal Conductivity of light-weight concrete

In order to understand the influence of the EPS beads and unprocessed FA on the improvement of thermal insulation properties of the developed light-weight concretes, their thermal conductivity λ [W/(m.°C)] was obtained using device ISOMET 2114 (Applied Precision, Ltd.). ISOMET 2114 is a multifunctional instrument for measuring thermal conductivity, thermal diffusivity, and volumetric heat capacity. The measurement is based on the analysis of the temperature response of the analyzed material to heat flow impulses. The heat flow is induced by electrical heating using a resistor heater having a direct thermal contact with the surface of the sample. LWC-samples with the side dimension of 70×70×70 mm were measured using a surface probe. Before the measurements, all specimens were dried at 100 ± 5 °C.

The measurements on both reference and pre-treated specimens were performed in the laboratory condition at 20 ± 5 °C and (30 ÷ 40) % relative humidity.

Testing procedures

In this study, uniaxial compressive tests on LWC samples (for each concrete sample) were performed with a constant loading rate of 500 N/s on system Controls Advantest 9 (Figure 7). The reason of choosing 500 N/s is to keep the loading rate to a minimum in the comparison of test LWC results.

2.4. Experimental Plan

Figure 8 shows the structure of the experimental plan. In this experimental program design, the determination of the concrete mixture compositions is according to the absolute volume method and the definition of temperature distribution over the thickness of the experimental wall structure is using the computer program ANSYS 18, which is the basis for comparison of thermal insulation performance in the structure of wall cover. The ANSYS computer program, based on the finite-element method, will analyze the thermal insulation performance of the object study.

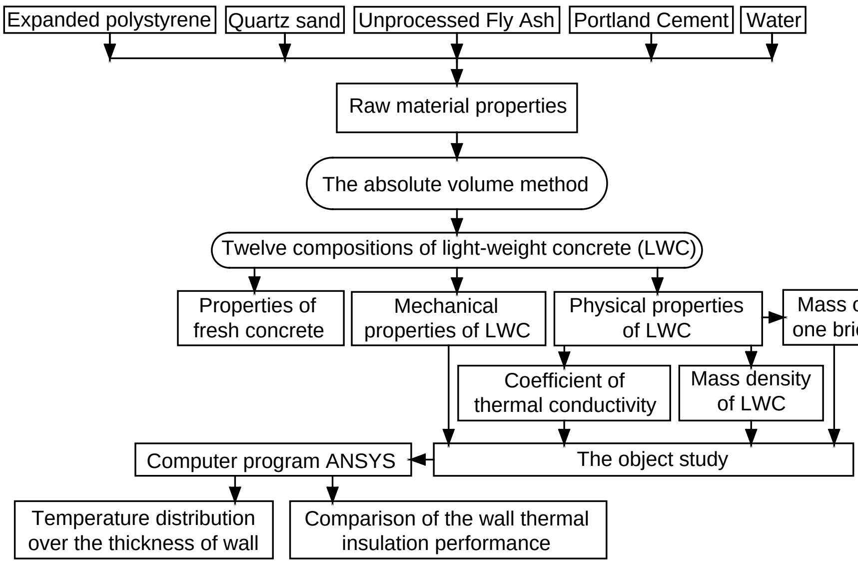


Figure 8. Experimental program

2.5. Fundamentals of the heat transfer theory in material and polystyrene concrete blocks

According to [28], the heat transfer equation in the wall is determined by formula (1):

$$\frac{\partial}{\partial x}\left(\lambda_x \frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda_y \frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda_z \frac{\partial T}{\partial z}\right)=\rho c\frac{\partial T}{\partial t}, \quad (1)$$

where T(x, y and z) is temperature in coordinates (x, y and z) (°C);

λ_x, λ_y, λ_z are thermal conductivity coefficients of concrete along the x, y, z axes W/(m.°C);

c is specific heat (kJ/kg.°C);

ρ is density (kg/m^3);

t is time (day).

To solve equation (1), it is necessary to know two main types of boundary conditions are Drichlet and Cauchy boundary [29, 30], which can be written respectively as:

$$T = T_s; \quad (2)$$

$$\lambda \frac{\partial T}{\partial n} = \alpha_n (T_s - T_a), \quad (3)$$

where λ is thermal conductivity W/(m.°C);

n is the surface normal direction;

T_s is the temperature of cement mortar surface (°C);

T_a is atmospheric temperature (°C);

α_n is represented surface heat transfer coefficient (W/m^2.°C).

The problem of transfer heat through a wall structure, which is not a homogeneous material, is a complex problem. Therefore, appropriate methods often are used in the determination of heat transfer through the structure. In recent years, the most complete factor consideration for temperature problem solution possibly applies numerical methods, particularly, the finite element method through ANSYS, ADINA, ABAQUS, MIDAS CIVIL programs and others [30–33].

In this study analyze the thermal performance evaluation of the wall using complex computer program ANSYS 18, which is one of the modern programs, allowing users to put in necessary data, for example: thickness, physical and mechanical characteristics, etc. So that the results are approximate to the empirical results.

2.6. The object study

The objective of the current study was light-weight concrete for the production of the wall cover with size 1000x1000x250 mm, which is located at the cover of the High-Rise buildings and direct contact with the sun, considered at the time of June in North Vietnam. The basic properties of some types of materials are used in the analysis of heat transfer through the building wall coverings and are shown in Table 3. In this paper consider a block of this wall with two layers of mortar of thickness 15 mm (shown in Figure 9).

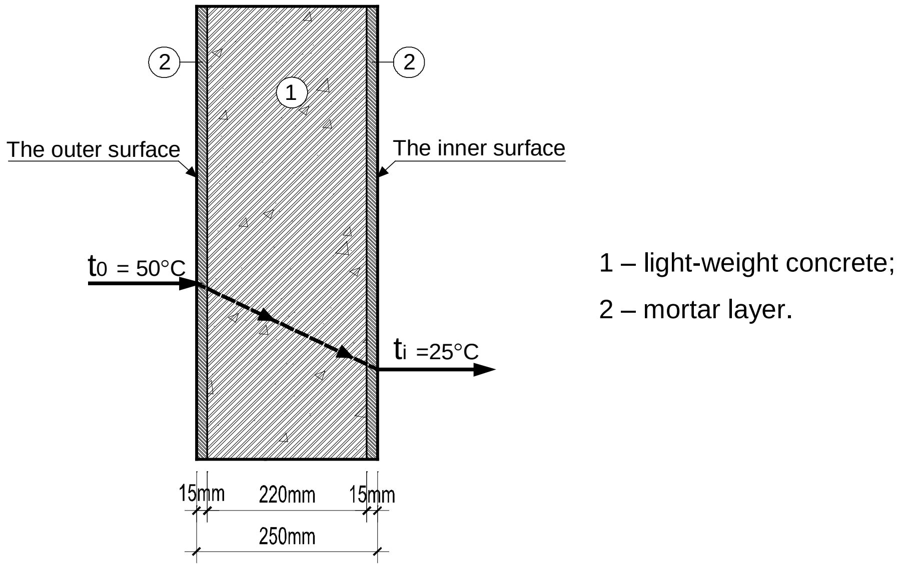
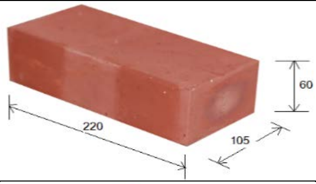
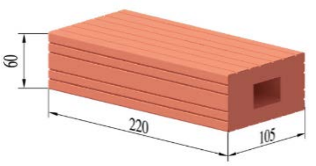
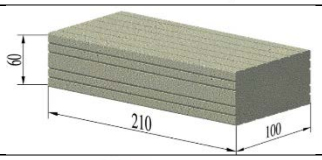
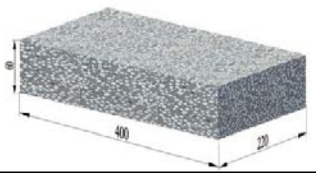


Figure 9. The wall cover, thickness 220 mm and two layers of mortar thickness 15 mm.

In standard TCVN 4605-1988 [6] «Heating techniques – Insulating component – Designs standard» is shown when considering solar radiation factors and other conditions, the estimated outdoor temperature is determined by: $t_0 = t_n + \varphi . I_{tb} / \alpha_n = 49.64$ °C ≈ 50 °C with the outside temperature of the building $t_n = 40$ °C in the summer, the heat transfer coefficient of the outer surface of the enclosing structure of the wall $\alpha_n = 25$ (W/m^2.°C); solar radiation intensity on average on the wall's surface $I_{tb} = 366$ W/m^2 and absorption coefficient of outside surface (cement mortar) $\varphi = 0.65$.

The temperature of the outer (t_o) and inner (t_i) surfaces of the building's wall covering is $t_o = 50$ °C, $t_i = 25$ °C and the heat transfer coefficient of the inner surface of the enclosing structure $\alpha_t = 5.9$ W/m^2.°C (in Table 3 – TCVN 4605-1988 [1]). In this case, the moisture of the materials not is considered in numerical simulation of heat transfer in the walling structure.

Table 3. Material properties in thermal behavior analysis.

No.	Materials	Figures	Physical properties of materials		
			Coefficient of thermal conductivity λ (W/(m.°C))	Mass density (kg/m^3)	Mass of one brick (kg)
1	Solid clay brick [6]		0.81	1600	2.218
2	Hollow clay brick [6]		0.52	1350	1.6
3	Solid unit with slag concrete [5, 6]		0.7	1200	1.663
4	Solid brick with light-weight concrete 400×220×60 mm [60 % EPS and 40 % FA in Table 8]		0.275	785	4.145
5	Cement mortar [6]		0.93	1800	

2.7. Calculation of the concrete mixture compositions

It is necessary to determine the concrete mixture compositions for the light-weight concrete production, which are intended for light-weight concrete blocks with low thermal conductivity in the High-Rise Construction in Northern of Vietnam. The initial ratios of raw materials by weight in concrete mixtures for the production of light-weight concrete are given in Table 4.

Table 4. Ratios of raw materials used in preliminary composition.

Ratios	EPS (%volume fresh concrete)	$\frac{FA}{OPC}$	$\frac{W}{BID}$	$\frac{QS}{BID}$	$\frac{SF}{OPC}$	$\frac{SR5000}{OPC}$	Volume of air in concrete
Value	30 ÷ 60	0.2 ÷ 0.4	0.3	1.2	0.1	0.02	2 %

Note: *BID – binder: BID = OPC + FA + SF.*

Based on the characteristics of the raw materials and the ratios above, together with combined the Bolomey-Skramtaev equation, after solving the optimization problem and adjusting results experimentally in the laboratory, water-binder ratio of this light-weight concrete, with maximum compressive strength at 28-day of 30 MPa and dry unit weight of 800÷1500 kg/m^3, was obtained $\frac{W}{BID} = 0.3$. Using the absolute volume method were obtained the compositions of specimens used in this work can be found in Table 5.

Table 5. Ingredient proportions for the preparation of concrete samples.

Sample ID.	The rate of components			Concrete mixture compositions (kg/m^3)						
	$\frac{W}{BID}$	EPS (%)	$\frac{FA}{OPC}$	OPC	FA	SF	QS	SR5000	W	EPS
LWC-30EPS-0.2FA	0.3	30	0.2	470	94	47.0	733	9.40	183	5.43
LWC-30EPS-0.3FA			0.3	434	130	43.4	730	8.69	182	5.43
LWC-30EPS-0.4FA			0.4	404	162	40.4	727	8.08	182	5.43
LWC-40EPS-0.2FA		40	0.2	401	80	40.1	625	8.02	156	7.24
LWC-40EPS-0.3FA			0.3	371	111	37.1	622	7.41	156	7.24
LWC-40EPS-0.4FA			0.4	344	138	34.4	620	6.89	155	7.24
LWC-50EPS-0.2FA		50	0.2	332	66	33.2	517	6.63	130	9.05
LWC-50EPS-0.3FA			0.3	307	92	30.7	515	6.13	129	9.05
LWC-50EPS-0.4FA			0.4	285	114	28.5	513	5.70	128	9.05
LWC-60EPS-0.2FA		60	0.2	263	53	26.3	410	5.25	103	10.86
LWC-60EPS-0.3FA			0.3	243	73	24.3	408	4.85	102	10.86
LWC-60EPS-0.4FA			0.4	226	90	22.6	406	4.51	102	10.86

Note: $\frac{W}{BID}$ *and* $\frac{FA}{OPC}$ *ratio by weight and the volume of air of 2 % volume of concrete.*

Additionally, the twelve of the material compositions in the dry state of the light-weight concrete mixtures with varying amounts of EPS beads and unprocessed FA were made for this experiment as in Table 5. On the one hand, the volume of fresh concrete was replaced with 30 %, 40 %, 50 % and 60 % by volume of EPS beads [25, 34]. On the other hand, the ordinary Portland cement was replaced with 20 %, 30 % and 40 % by mass of FA TPP «Vung Ang» [35].

According to [23, 24], choosing lower substitutions of EPS in concrete mixture is within satisfactory limits. However, one of the main goals of the present work is to utilize as much EPS beads as possible, solving the disposal problem of waste expanded polystyrene foam and producing light-weight concrete blocks with low thermal conductivity in construction the High-Rise buildings.

In the case of this research, the ratios $\frac{W}{BID}$ and $\frac{SR5000}{OPC}$ of 0.3 and 0.02 respectively were kept constant for all mixtures and no adjustment to the water content was made for all mixtures. The superplasticizer SR 5000F «SilkRoad» has been used to reduce the $\frac{W}{BID}$ ratio and to increase workability of concrete mixtures.

3. Results and Discussion

3.1. Properties of fresh concrete

The average density of fresh concretes and the slump values for light-weight concretes containing varying amounts of EPS beads and Unprocessed FA are presented in Table 6 and Figure 10. The density values of concrete mixtures were in the range of 849÷1537 kg/m^3. The slump values were between 14.5 and 20.5 cm.

The consistency of the concretes containing (30 ÷ 60) % EPS beads was almost satisfying, and compaction and finish-ability processes were not easily achieved, but the consistency of all other mixtures were normal to work with, and casting, compaction, and finish-ability processes were performed easily. By increasing the EPS content, the slump values of the concrete mixtures increased but the average density of fresh concretes decreased. This was mainly due to the low water absorption of EPS compared with natural aggregate and the density value was much less than that of natural materials. In addition EPS beads are hydrophobic and resist absorption of the mixture's water.

3.2. Mechanical properties of light-weight concrete samples

The mechanical properties of light-weight concrete containing varying contents of EPS and unprocessed FA at different curing times are shown in Table 7. The compressive strength of the concrete sample was in the range of 4.08÷31.2 MPa at 28 days curing time. At this age, tensile strength and modulus of elasticity values were, respectively, in the range of 0.52÷2.45 MPa and 3266÷16855 MPa.

Table 6. Properties of fresh concrete mixtures.

Sample ID.	$\frac{W}{BID}$	EPS (%)	$\frac{FA}{OPC}$	Fresh unit weight (kg/m^3)	Slump (cm)
LWC-30EPS-0.2FA	0.3	30	0.2	1537	16.5
LWC-30EPS-0.3FA			0.3	1528	15.0
LWC-30EPS-0.4FA			0.4	1519	14.5
LWC-40EPS-0.2FA		40	0.2	1311	18.0
LWC-40EPS-0.3FA			0.3	1296	17.0
LWC-40EPS-0.4FA			0.4	1288	16.5
LWC-50EPS-0.2FA		50	0.2	1083	19.5
LWC-50EPS-0.3FA			0.3	1051	18.5
LWC-50EPS-0.4FA			0.4	1045	17.0
LWC-60EPS-0.2FA		60	0.2	862	20.5
LWC-60EPS-0.3FA			0.3	854	19.0
LWC-60EPS-0.4FA			0.4	849	19.5

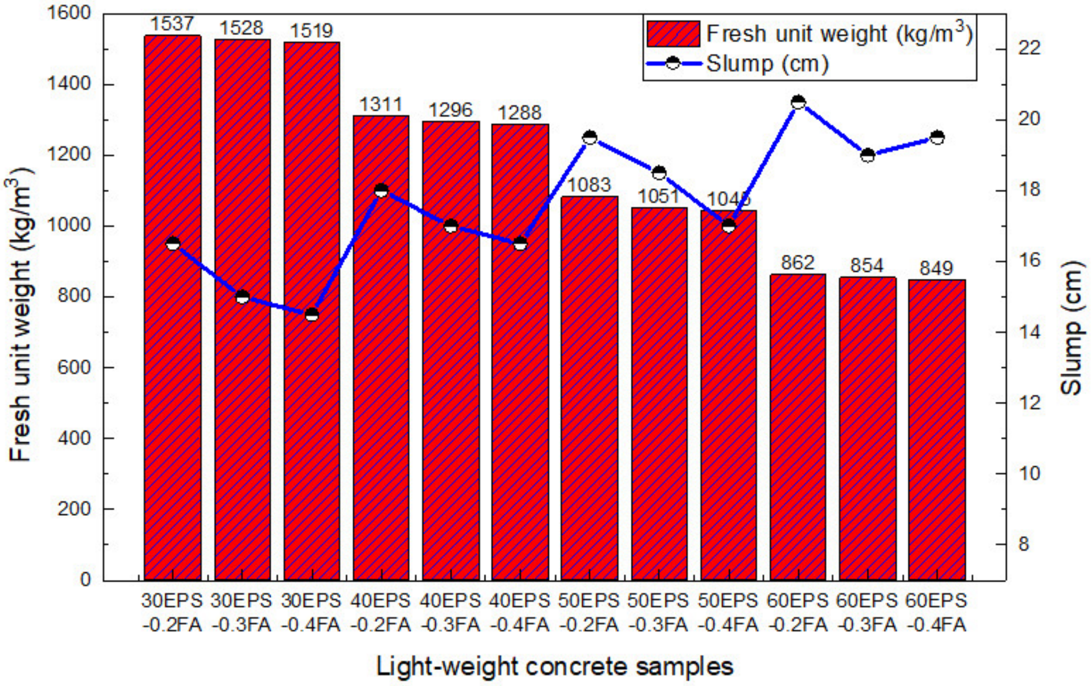


Figure 10. Effect of unprocessed Fly Ash and Expanded polystyrene on density and workability of mixtures concrete.

Table 7. Mechanical properties of light-weight concrete at different curing ages.

Sample ID.	Compressive strength at different ages (MPa)						Flexural strength at the age of 28 days (MPa)	Modulus of elasticity at 28 days (MPa)
	1 days	3 days	7 days	14 days	28 days	56 days		
LWC-30EPS-0.2FA	5	12.5	20.3	26.8	31.2	33.95	2.45	16855
LWC-30EPS-0.3FA	4.5	11.2	18.3	24.5	28.1	32.44	2.35	15811
LWC-30EPS-0.4FA	3.6	9	14.6	20.3	24.3	26.56	2.08	14135
LWC-40EPS-0.2FA	2.3	5.7	9.3	12.8	14.3	17.41	1.89	10548
LWC-40EPS-0.3FA	2.1	5.4	8.7	12.1	13.1	15.98	1.56	9224
LWC-40EPS-0.4FA	1.6	3.9	6.4	8.9	10.9	14.33	1.52	8272
LWC-50EPS-0.2FA	1.5	3.7	6	7.5	9.3	12.5	1.24	6295
LWC-50EPS-0.3FA	1.1	2.9	4.6	6.4	7.2	10.56	1.15	5135
LWC-50EPS-0.4FA	0.78	1.7	2.7	3.7	4.2	5.11	1.08	4387
LWC-60EPS-0.2FA	0.71	1.85	2.65	3.34	4.18	4.56	0.64	3900
LWC-60EPS-0.3FA	0.62	1.67	2.33	2.87	4.11	4.25	0.58	3606
LWC-60EPS-0.4FA	0.56	1.62	2.28	2.73	4.08	4.15	0.52	3266

Similar to the results presented in published studies [36-38], the strengths are decreased as the EPS beads and unprocessed FA contents in concrete samples are increased. For example, the compressive strength for the control concrete (30 % EPS + 20 % FA) was 31.2 MPa at 28 days of age and these decreased to 4.08 MPa for the concrete containing 60 % EPS + 40 % FA at the same age; the decrease in strength concrete was about 86.9 %.

The relationship between compressive strength and curing age for light-weight concrete shown in Figure 11.

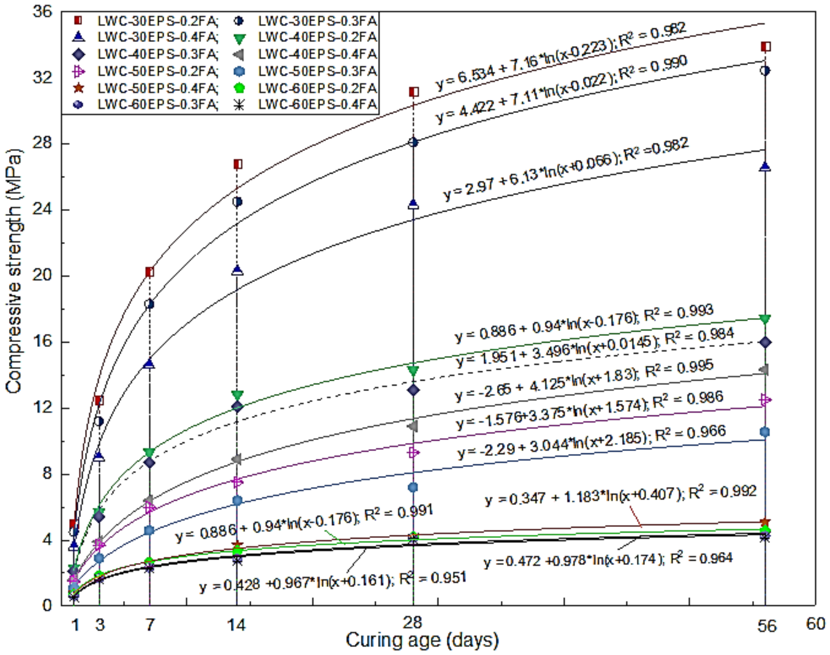


Figure 11. Compressive strength development of light-weight concrete at different ages.

The Portland cement concrete strength level and rate of gain are dependent on many factors. Hydration rate and percentage are two factors related to the used cement [39]. Besides the used cement, there are many factors contributing to both of strength level and its rate of gain at different ages. Mix composition, aggregate type and properties, temperature degree, curing time and method are some factors among the factors affecting both strength level and the gain rate at different ages of concrete [40].

According to experimental results, for all proportions of light-weight concrete, the relationship between age and the compressive strength could take the following shape:

$$y = A + B^* \ln (x + C). \tag{4}$$

where: y is the compressive strength of concrete (MPa) at age (x) days and (A), (B) and (C) are constants. These results, similar to the results presented in published studies [39–41].

It could be noticed that, for mixes of concrete containing 30 %, 40 %, 50 % and 60 % by volume of EPS beads and 20 %, 30 % and 40 % by mass of FA follow the proposed formula (4) with a correlation coefficient more than 95 % ($R^2 > 0.95$). The values of coefficients (A, B and C) for mixes containing EPS beads and FA seem to be different.

The relation between compressive strength (R_{cf}, MPa) and tensile strength (R_{ts}, MPa) of light-weight concrete is shown in Figure 12.

The empirical equation obtained for LWC with correlation coefficient ($R^2 = 0.9515$) is given as:

$$R_{cf} = 5.577 R_{ts}^{1.886} \tag{5}$$

For light-weight concrete, the modulus of elasticity was determined from the empirical formula proposed by the ACI 318-14 [42, 43] commission, as specified below:

$$E_c = 43 \times \rho^{1.5} \sqrt{R_{cf}}, \tag{6}$$

where: E_c – modulus of elasticity (MPa); R_{cf} – compressive strength (MPa); ρ – dry density (kg/m³).

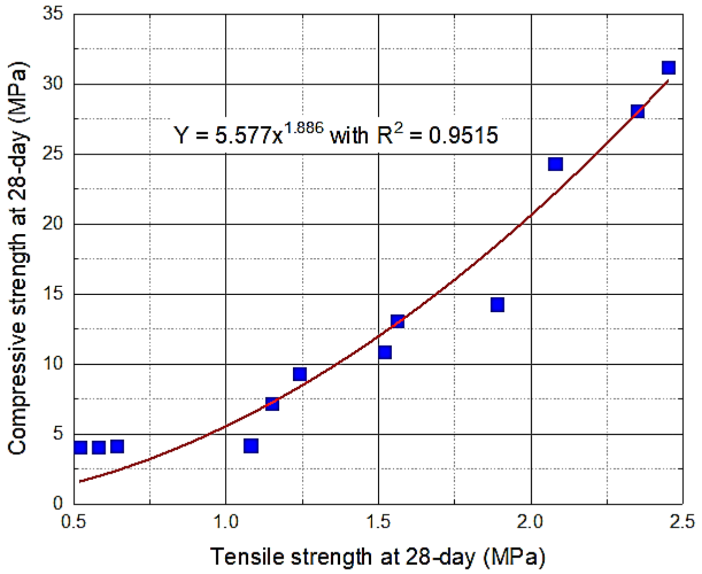


Figure 12. Correlation between compressive strength and tensile strength of light-weight concrete.

Equation (6), which relates the modulus of elasticity with the compressive strength of LWC was chosen because it also takes into account the density of the light-weight concrete. According to the results presented in study [44], the correlation between modulus of elasticity, compressive strength and density of LWC was determined from the empirical formula (7):

$$E_c = 70 \times \rho^{1.53} \times R_{cf}^{0.25} \text{ (MPa)}. \quad (7)$$

Based on the results of this study, the modulus of elasticity of the LWC at 28 days appears to increase with the increase in multiplier dry density and compressive strength of specimens. The relationship between modulus of elasticity, compressive strength and dry density of light-weight concrete made with different ESP beads and unprocessed FA contents is illustrated in Figure 13 and shown in formula (8):

$$E_c = 3.848\rho * \sqrt[3]{R_{cf}} - 1643.64 \text{ (MPa) with } R^2 = 0.993. \quad (8)$$

The value R^2 = 0.993 of Equation (8) represents a very strong negative correlation between the three compared parameters of the modulus of elasticity, compressive strength and dry density for the LWC incorporating different amounts of ESP beads and unprocessed FA.

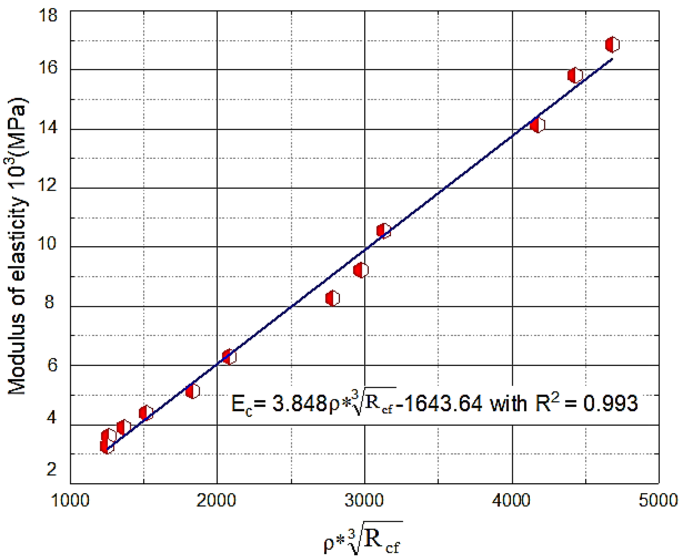


Figure 13. Correlation between modulus of elasticity, compressive strength and density of light-weight concrete.

3.3. Basic physical properties of tested light-weight concrete

The basic physical properties of light-weight concrete containing different contents of EPS beads and unprocessed FA is presented in Table 8. The density values were in the range of 782.42÷1487.1 kg/m³, water absorption 10.5÷14.8 % and thermal conductivity 0.275 ÷ 0.651 W/m.ºC.

Table 8. The basic physical properties of light-weight concrete specimens.

Sample ID.	Dry density (kg/m³)	Water absorption (%)	Thermal conductivity λ (W/m.ºC)
LWC-30EPS-0.2FA	1487.1	10.5	0.651
LWC-30EPS-0.3FA	1457	11.8	0.656
LWC-30EPS-0.4FA	1441.9	11.85	0.638
LWC-40EPS-0.2FA	1289.7	12.5	0.560
LWC-40EPS-0.3FA	1261.9	13.2	0.541
LWC-40EPS-0.4FA	1254.7	13.5	0.548
LWC-50EPS-0.2FA	989.5	13.8	0.402
LWC-50EPS-0.3FA	948	14	0.371
LWC-50EPS-0.4FA	940.2	14.2	0.387
LWC-60EPS-0.2FA	846.92	14.3	0.339
LWC-60EPS-0.3FA	787.38	14.5	0.298
LWC-60EPS-0.4FA	782.42	14.8	0.275

The relationship between the dry density and water absorption of light-weight concrete made with different ESP beads and unprocessed FA contents is illustrated in Figure 14. The dry density of the LWC appears to decrease with an increase in water absorption of specimens. A linear function appears to better describe the relationship between dry density and water absorption for all concretes made with different EPS beads and FA contents at 28 days and is shown in Equation (9):

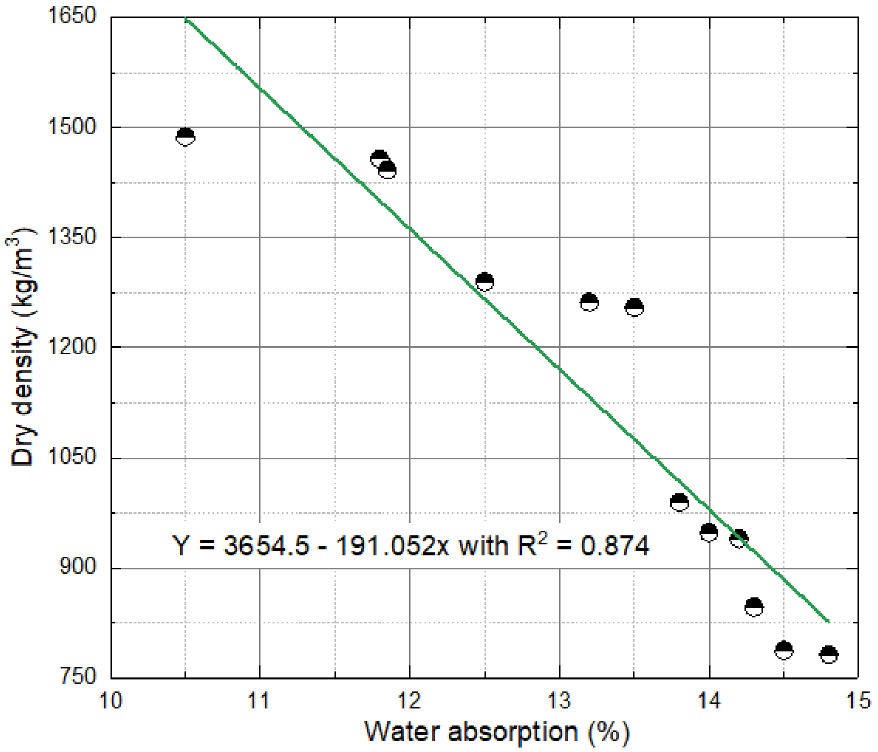


Figure 14. Relationship between dry density and water absorption of light-weight concrete.

$$Y = 3654.5 - 191.052x \text{ with } R^2 = 0.874. \quad (9)$$

In Equation (9), Y is the dry density (kg/m³) and x is the water absorption (%). The value R^2 = 0.874 represents a relatively strong negative correlation between the two compared parameters of dry density and water absorption for the concrete incorporating different amounts of ESP beads and unprocessed FA.

The relationship between the thermal conductivity and dry density of LWC made with different ESP and FA contents are shown in Figure 15.

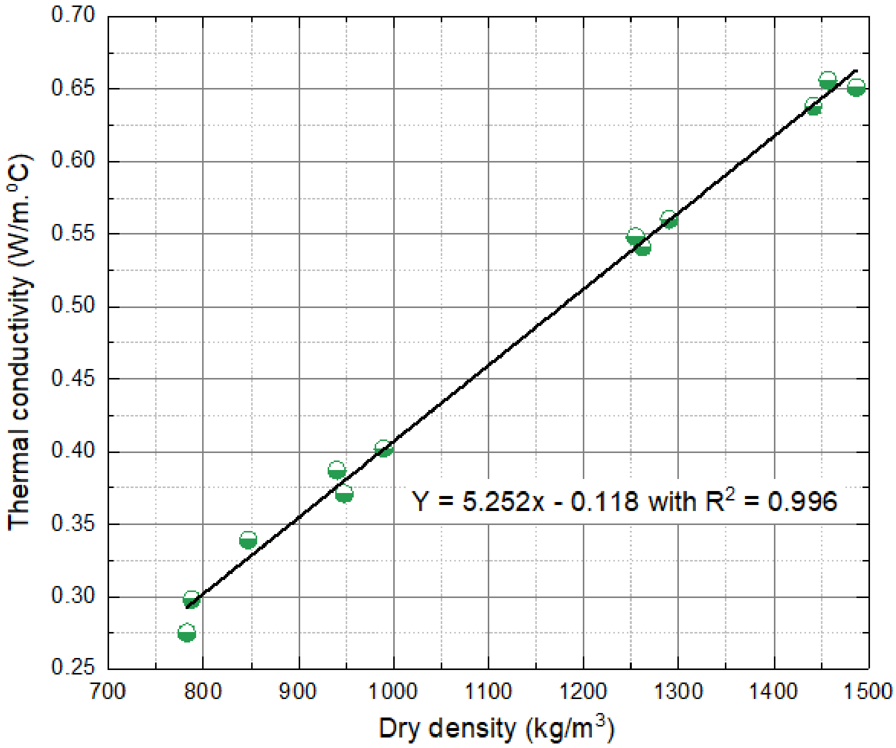


Figure 15. Relationship between thermal conductivity and dry density of light-weight concrete.

The dry density of the LWC appears to increase with an increase in thermal conductivity of LWC. Based on the results of the studies [45] for structural insulation of polystyrene concrete, a generalized dependence of thermal conductivity on dry density was proposed, which was approximated by a linear dependence according to the formula (10):

$$\lambda^{LWC} = 0.4228*\rho^{LWC} - 42.281 \text{ with } R^2 = 0.9515. \quad (10)$$

For this study, a linear function appears to better describe the relationship between thermal conductivity and dry density of light-weight concrete made with different EPS beads and FA contents at 28 days and is shown in Equation (11):

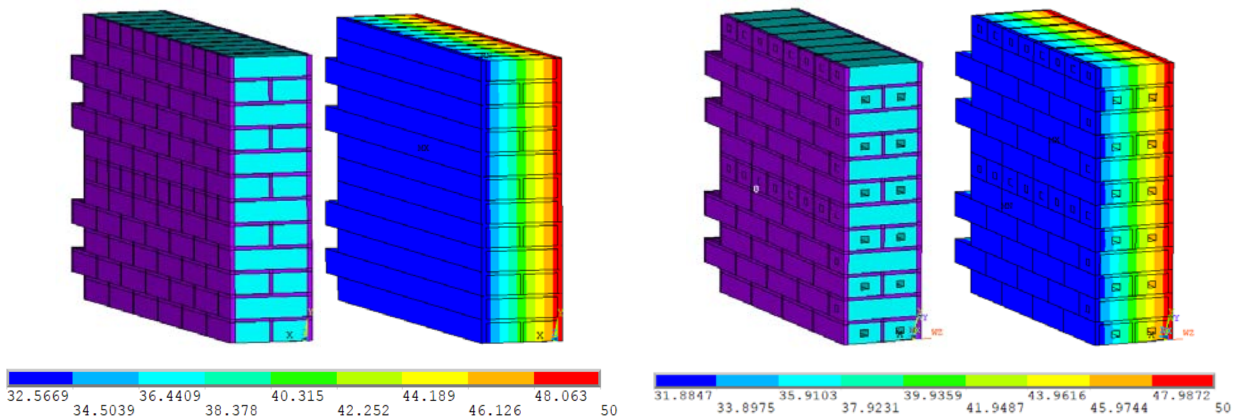
$$Y = 5.252x - 0.118 \text{ with } R^2 = 0.996. \quad (11)$$

The first (Y) and second (x) terms in equation (11) represent thermal conductivity (W/m.ºC) and the dry density (kg/m³) of LWC, respectively. The value R^2 = 0.996 represents a very strong negative correlation between the two compared parameters of thermal conductivity and dry density for the LWC incorporating different amounts of ESP beads and unprocessed FA.

3.4. Definitions of temperature regime and comparison of thermal insulation performance of light-weight concrete block with the standard brick in enclosing structures

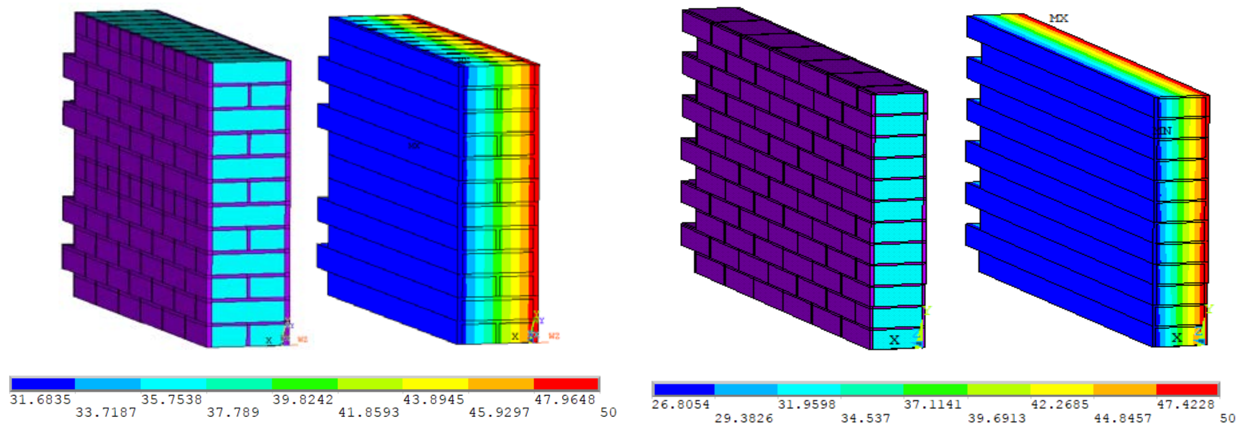
This study analyzes the heat transfer in the wall covering of buildings, which are built by block bricks light-weight concrete (which consist of 60 % EPS and 40 % FA, shown in Table 8), with the using a complex computer program ANSYS 18 (APDL). These analyzes allow for the assessment and comparison of the insulation of the wall covering made of light-weight concrete with wall coverings made from other materials.

The results of the analysis of the heat transfer through the wall coverings, which were constructed of solid clay brick, hollow clay brick, solid unit with slag concrete and solid brick with LWC, are shown in Figures 16, 17 and 18.



(a) (b)

Figure 16. Temperature distribution over the thickness of wall: (a) by the solid clay brick and (b) by hollow clay brick.



(a) (b)

Figure 17. Temperature distribution over the thickness of wall: (a) by solid unit with slag concrete and (b) by solid brick with LWC.

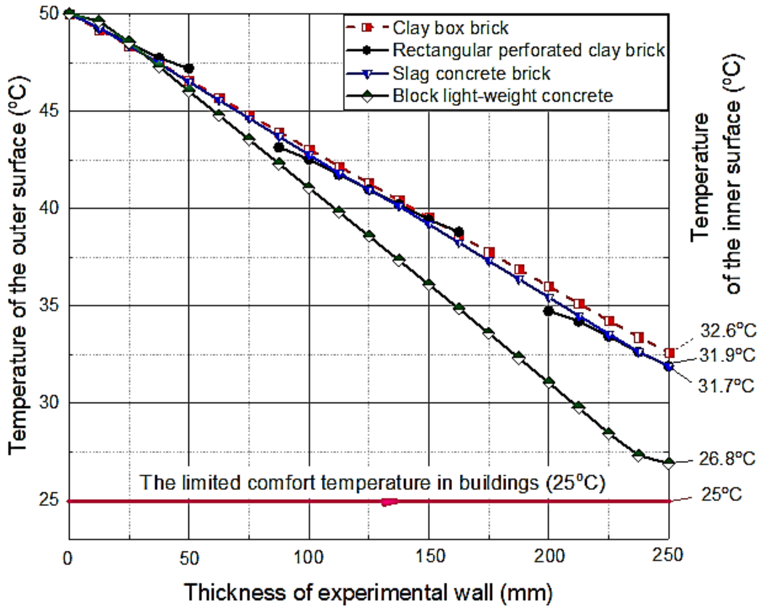


Figure 18. Comparison chart of heat distribution over the thickness of the experimental wall structure.

Based on the results, the analysis by ANSYS 18 software are shown that at the same thickness of 250 mm, a wall with the solid bricks with LWC has better insulation than the wall made of other materials such as: solid clay brick, hollow clay brick, solid unit with slag concrete.

By comparison, the comfort temperature in buildings (25 °C), the temperature of the inner surface of the experimental wall structure was increased 1.8 °C by solid brick with LWC; 7.6 °C by solid clay brick; 6.9 °C by clay hollow bricks and 6.7 °C by solid unit with slag concrete. Temperature of the inner surface of the experimental wall structure was increased not much, so the energy cost to reduce temperature in building will be lower than other wall solutions. In addition, the size of the block bricks from light-weight concrete is four times larger than that of the other bricks. The weight of a solid brick with LWC larger than 2 times the other bricks. The size of the large brick, while the weight of the brick is small. This will create favorable conditions and shorten construction time.

4. Conclusion

Based on the experimental results, the following conclusions may be drawn:

1. By increasing EPS beads and unprocessed FA in the twelve of compositions for light-weight concrete the strength, modulus of elasticity, dry density and thermal conductivity decreased, but its water absorption and thermal insulation performance increased. The level of decrease in the mechanical properties of LWC depends upon the replacement level of ESP and FA.

2. The concrete containing 60 % EPS and 40 % FA of contents can be used to produce light-weight bricks and concrete blocks with low thermal conductivity at the wall covers of the High-Rise buildings in Vietnam or may be used in low-strength concretes' applications for example footpaths, cycle paths, and noise reduction barriers in the music room and the study room.

3. The use of EPS beads and unprocessed FA (Vietnam) is an interesting way to extend its life in civil engineering applications providing light-weight concretes with enhanced thermal insulation properties and environmentally-friendly materials.

4. According to the results, the wall with block light-weight concrete bricks with low thermal conductivity is a rational, technological constructing solution under the climatic conditions of Vietnam, which allows providing the required parameters of the microclimate, creating a comfortable mode for indoor-life.

5. The advantages of the investigated block light-weight brick concrete design compared to traditional solutions are: increasing thermal uniformity due to the reduction of heat-conducting inclusions and increasing manufacturability by reducing the duration and complexity of work.

When EPS beads are manufactured correctly, with appropriate concrete mix design, the utilization of this novel fine, coarse and lightweight aggregate is made from EPS beads and unprocessed FA in light-weight concrete production is possible. However, more corrosion and mechanical experiments, resistivity, the specific heat of LWC and effect of the bond between the coating and waste EPS as future work needed to be done before this novel environmentally-friendly material could be used in different buildings and structures.

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