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Strength and thermal properties of unfired four-hole hollow bricks manufactured from a mixture of cement, low-calcium fly ash and blended fine aggregates

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Abstract. This study develops a new type of eco-friendly building brick so-called unfired four-hole hollow brick (UFHB) by using a mixture of ordinary Portland cement (OPC), low-calcium fly ash (FA), and different proportions of crushed sand (CS) and river sand (RS). A hydraulic-static pressure was applied to form the brick samples. The effect of various CS-RS blends on the mechanical strength of the UFHB samples was studied. In addition, the numerical method was applied to simulate the heat transfer process through the brick wall. The obtained results show that the UFHB mixture containing a mixture of 10% RS and 90% CS as blended fine aggregate registered the highest strength value in comparison with other UFHB mixtures. Moreover, utilization of the UFHB was highly effective in term of heat insulation as compared to the conventional brick.

1. Introduction

The rapid development of construction industry requires a variety of construction materials in a large quantity, especially the demand of building brick. The heat transferring is one of the factors that is mostly considered by both the designer and the user during either the construction process or the use of any building. The wall of a building plays an important role in insulating between the internal and external sides and its primary function is to cover and protect the building from outside factors such as wind, heat, etc. However, the characteristics of the wall rely heavily on the properties of brick inside it. These bricks not only sustain the wall's loading but also supply the great insulation for the building. Recently, more attention has been paid to unfired materials with good physical properties that can fulfill all requirements of strength and serviceability for thermal transmittance. Several scientific publications have been adverted to fire resistance and thermal behavior of a brick or a brick wall, e.g. Bondi and Stefanizzi [1] reported on the hygrothermal performance of hollow bricks; Al Nahhas et al. [2] conducted an experimental and thermal modeling on the resistance to fire of walls constituted by hollow blocks, with the results highlighted the phase change effect under high temperature; Sala et al. [3] performed both the laboratory experiments and numerical analysis on static and dynamic thermal characterization of a hollow brick wall. Besides, the production of conventional brick has been facing

with more and more challenges, especially the shortage of natural resources, environmental pollution, and energy consumption. Hence, the development of unfired building brick to replace the conventional one is strongly encouraged. Follow this trend, this study develops unfired four-hole hollow brick (UFHB), a new type of eco-friendly unfired building brick, by using small amounts of OPC and FA with a large proportion of CS and RS. The effect of various CS-RS blends on the compressive strength of the UFHB was investigated. The heat transfer process through the brick wall was also studied.

2. Materials and experimental details

2.1. Materials
Type-PCB40 OPC and low-calcium FA, with characteristics as given in Tables 1 and 2, were used as binder materials, whereas crushed sand (CS) and natural river sand (RS) were used as fine aggregates for this experimental work. Both CS and RS had the respective densities and water absorption (WA) rates of 2.47 and 4.51% and 2.55 and 1.72%. In order to study the effect of aggregate gradation on mechanical properties of bricks, blended CS-RS mixtures as displayed in Figure 1 were especially used. It can be seen that the existence of RS with small particle size modified and reformed the gradation curve and fineness modulus (FM) of the original aggregate.

Table 1. Physical properties of powder materials.

Items	OPC	FA
Specific gravity	3.15	2.29
Mean particle size (μm)	19.1	21.5
Specific surface area (m^2/g)	0.78	0.66
Strength activity index at 28 days (SAI, %)	100	86.5

Table 2. Chemical compositions of powder materials.

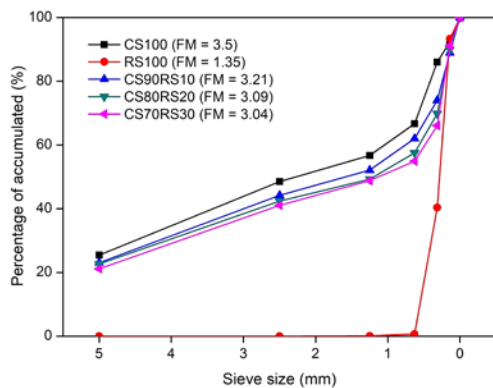| Materials	Chemical compositions (wt.%)							
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O
OPC	20.04	4.24	3.12	62.43	4.17	2.97	0.43	0.33
FA	64.01	22.14	5.64	2.75	0.92	0.61	1.36	0.85

Figure 1. Gradation curves of fine aggregate.

Figure 2. UFHB samples.

2.2. Mix proportioning
In this study, the influence of fine aggregate gradation on the mechanical strength of the UFHB was assessed by using various CS-RS blends. Different percentages of CS (100%, 90%, 80%, and 70%) and RS (0%, 10%, 20%, and 30%) were mixed together to prepare the blended aggregate before making the UFHB samples. A mixture of OPC and FA was used as a binder material at a fixed content of 25% by weight of total mixture. A constant water-to-binder (w/b) ratio of 0.2 was applied for all brick mixtures. The mixture proportions for the preparation of the UFHB samples are given in Table 3.

Table 3. Material proportions for preparing brick samples.

Ingredients (kg/m^3)	UFHB mixtures			
	F15R00	F15R10	F15R20	F15R30
OPC	268.6	268.8	269.0	269.2
FA	335.8	336.0	336.3	336.5
CS	1634.2	1411.3	1188.1	964.6
RS	0.0	224.0	448.3	673.0
Water	120.9	121.0	121.1	121.1

2.3. The preparation of brick samples and experimental methods

According to the designed proportions as presented in Table 3, the 80×80×180 mm UFHB samples were manufactured at a local brick production factory. Herein, a brick's automated production line was used to produce the UFHB samples as shown in Figure 2. It is noted that a hydraulic pressure of about 4.7 MPa was applied to form the samples. The finished bricks were placed in open air for 24h then immersed in water for a haft hour. After that, the bricks were covered by a thin plastic film and stored in the humidity-curing room for 28 days. To evaluate the mechanical strength of the UFHB, the compressive strength test was carried out in accordance with TCVN 6477-2016 [4]. Moreover, the thermal behavior of the produced bricks was evaluated by the simulation of heat transfer across the brick wall.

2.4. Simulation of heat transfer across the brick wall

The basic theory of heat transfer can be presented through equation (1) [5]:

$$\frac{\partial T}{\partial t} = \alpha_T \nabla^2 T \tag{1}$$

Where: $\alpha_T = \lambda / (c.\rho)$ - diffusivity, m^2/s;

   c - specific heat, kJ/(kg.^{0}C);

   ρ - density, kg/m^3;

   λ - thermal conductivity;

   $\nabla^2 T = div(grad\ T)$ – Laplace temperature operator.

Applying boundary conditions [6] to solve equation (1):

$$T = T_{\text{outer envir.}} \text{ and } -\lambda \frac{\partial T}{\partial n} = h(T_s - T_{\text{inner room}}) \tag{2}$$

Where: $T_{\text{outer envir.}} = 38^0$C - the highest average ambient temperature in Southern Vietnam [7];

   n - the outward direction normal to the surface;

   h - heat transfer coefficient, (W/m^2.^{0}C);

   T_s - temperatures at the boundary nodal points of bick wall, ^{0}C;

   $T_{\text{inner room}} = 22^0$C - average temperature inside the room in use condition.
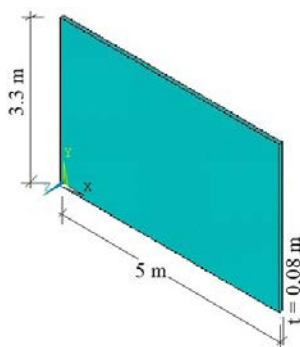

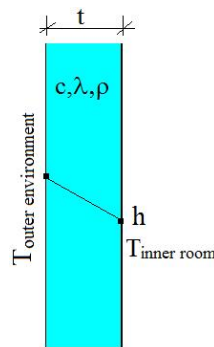**Figure 3**. Dimensions of brick wall model.

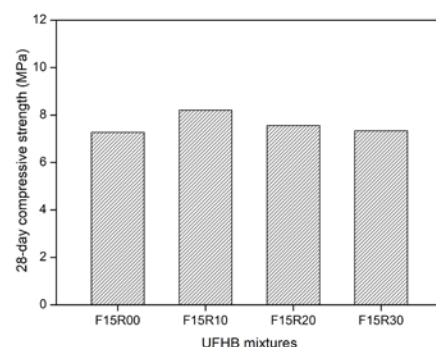**Figure 4**. The heat transfer through the brick wall model.

Figure 5. The 28-day compressive strength of UFHB samples.

The effect of convection in the air cavities of the brick holes compared to the air of the environment was shown to be negligible since the air (fluid) was almost still. Therefore, the convection in the air cavities of the brick holes was excluded from the final model. By the way, the computational analysis was simplified and acceptable [8]. In this study, modeling of the brick wall that measured $5.0{\times}3.3{\times}0.08$ m (Figure 3) under the influence of environmental temperature in Southern Vietnam was performed. For comparison purpose, it is assumed that two different types of brick, including UFHB and conventional reference brick (CRB), were used to construct the wall. The thermo-physical properties of these brick wall layers and the heat transfer model based on the finite element method (Ansys APDL) are shown in Table 4 and Figure 4, respectively.

Table 4. Thermo-physical properties of brick wall layers.

Thermo-physical properties	Values [9, 10]	
	UFHB	CRB
Thermal conductivity, λ [W/(m·^{0}C)]	0.78	1.25
Density, ρ (kg/m^3)	1900	2090
Specific heat capacity, C [J/(kg·^{0}C)]	1000	920
Convection coefficient, W/(m^2·^{0}C)	25	25

3. Results and discussion

3.1. Compressive strength

The variation in the compressive strength of the UFHB samples with different CS-RS proportions is shown in Figure 5. As the test result, the control mixture comprising 100% CS (F15R00) registered the lowest compressive strength value of 7.27 MPa. It is found that the use of blended CS-RS aggregates resulted in an increase in brick's strength as compared to the control sample. The UFHB samples containing 10% RS in combination with 90% CS had the highest compressive strength value of 8.21 MPa. However, the compressive strength was found to gradually decreasing with the increasing of RS content from 10% to 20% and 30%. In fact, the strength values of the UFHB samples with 20% and 30% RS contents were 7.56 MPa and 7.34 MPa, respectively. This increase in brick' strength was attributable to the filler effect of using RS, which contributed to refine the pores size and thus reduce the void volume within the brick structure. Another possible reason for the increasing strength of the bricks may be the formation of calcite within the cement-sand pore structure [11].

3.2. Thermal behavior of bricks

The temperature distribution during thermal flux through the two types of the brick wall as mentioned previously was analyzed using the famous Ansys APDL computer software, with the outcomes are displayed in Figures 6 and 7. It can be seen clearly that the temperature distribution through the thickness of both the CRB and UFHB walls was linear. The temperatures of about 26.0^{0}C and 27.6^{0}C were recorded at the inside surface of the UFHB and CRB walls, respectively. Thus, the UFHB was found to be more effective than the CRB under the same climate condition. Calculation of heat distribution across the brick wall is very useful to both the designer and the user in order to provide sufficient insulation solutions for each specific climate condition.
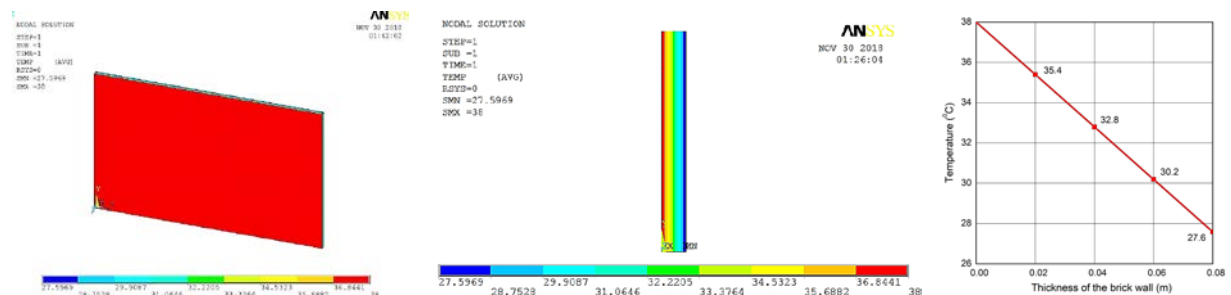

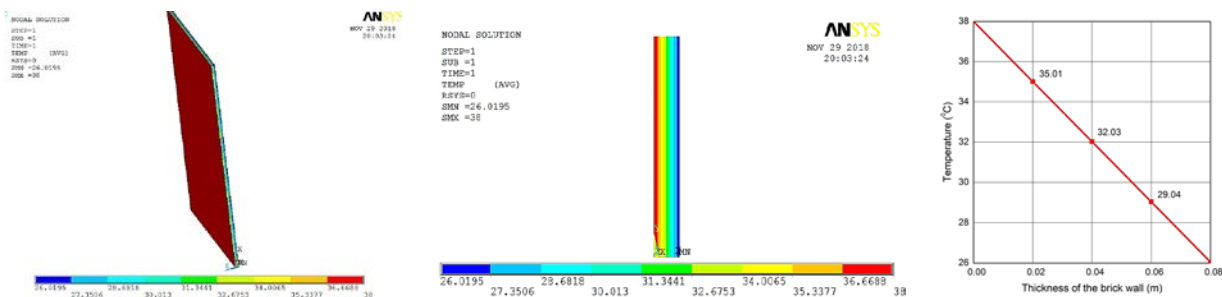
Figure 6. Temperature distribution on the CRB wall.

Figure 7. Temperature distribution on the UFHB wall.

4. Conclusions

The following conclusions can be drawn according to the simulation and experimental results:

1. The compressive strength of the UFHB samples was enhanced with an appropriate proportion of RS. This study found that the maximum brick's strength value of 8.21 MPa was achieved by using 10% RS- 90% CS blend and the strength value was declined at further RS addition. In real practice, the compressive strength of the brick is much dominant in comparison with other brick's properties.

2. Analyzing temperature distribution across the brick wall indicates that the use of the UFHB was more effective than using conventional brick in heat insulation aspect. The simulation results could be considered as good reference information in case of applying this type of brick in construction activities.

3. The findings of the present study demonstrate a high potential of using OPC, low-calcium FA, and CS-RS blends in the production of UFHB and further encourage the application of bricks in this type in the construction industry.

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