Lightweight Geopolymer Concrete Panels for a wall in high-rise buildings: Technical- Economical- Environmental efficiency

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Abstract. Brick and cement are two of the most used materials for a building wall, but the traditional brick and clinker production causes several environmental and human health impacts. Besides the demand of light-weight materials for the high-rise buildings is increasing more and more, these have encouraged the development of the new efficient materials to alternative the conventional brick. The objective of this study is to comparative technical and cost analysis as well as an environmental assessment of the wall structure used Lightweight Geopolymer Concrete Panels (LGCP). The results have revealed that the LGCP exhibits some superior engineering properties like as very low density and heat transfer coefficient, high strength,… The utilization of industrial wastes (fly ash-FA, Ground Granulated Blast furnace Slag-GGBS) as raw materials in LGCP production leads to reduce over 48% CO₂ emission, and up to 17 times energy consumption, but still cheaper 42% construction cost to conventional bricks. The LGCP application is an important step to contribute better environmentally-friendly in particular and reach a sustainable development of the construction industry in general.

1. Introduction
Over the past century, Clay-burn brick (CB) and Portland cement-based concrete have become the highest-volume manufactured product on Earth, due to the widespread availability and comparatively low cost of the raw materials [1]. However, their processing technologies consume a huge of raw materials like clay, shale, natural stone and sand has resulted in resource depletion, environmental degradation, and energy consumption [1, 2]. For example, to produce 1 billion standard bricks, it will take about 1.5 million m³ of clay, equivalent to 75 hectares of agricultural land (2m of mining depth) and 150,000 tons of coal, emitting about 0.57 million tons of CO₂ and many other harmful gases into the environment. The cement industry alone was estimated to be responsible for 5-10% of all anthropogenic CO₂ generated [1-5]. So that, the demand for sustainable development in the building materials industry is facing increased pressure to reduce environmental footprint through both manufacturing and operational phases, which is currently a key factor within the global housing and construction industry.

Along with the socio-economic development, there are more and more high-rise buildings are being constructed in Vietnam’s big cities. This results in a significant amount of materials for support and wall structures. Normally, materials cost could take 65-75% of the total construction cost [6]. In a high-rise building, the wall only plays as the partition and covering structures, but it has a very large
area and contributes up to 20-30% of the calculated load [7]. Therefore, the saving of materials and the use of high-quality, low-cost lightweight materials for load-bearing structures are the two priority targets in order not only reduces the dead load and increases material efficiency, but also contributes to reducing the construction costs.

Many types of light, high quality, and environmentally friendly bricks have been studied and applied in the world [7-12]. LGCPs made from geopolymer binder (or geopolymer foam) and expanded polystyrene aggregate with or without two calcium silicate surface layers [10-15]. These are considered as a new family of eco-sustainable masonry units because they widen the possibilities to recycle waste to useful products, especially build waste of construction and demolition processes. LGCP has been tested in the prototype scale that has been tested in the laboratory [6, 18]. The product has countless advantages compared to other wall panels and solid brick such as light and thin [6, 17]; high strength and impact resistance [6]; heat and sound insulation [7,8]; fireproof and waterproof [7,8]. Main products are used for both internal partitions and external walls. The product is the best substitute for traditional burn bricks and unburnt bricks.

Although LCGW is a promising material to replace to the orginal brick, there is a need for more information about its technical- economical- environmental efficiency in the high-rise building, before the innovation process can be scaled-up in Vietnam. This paper focuses on analysis and quantity assessment of technical properties, and the economic- environment efficiency of LGCP as wall structure in both multi- floors and high-rise buildings.

2. LGCP properties and research methodologies

2.1. LGCP properties

Table 1 illustrates the properties of LGCP products [6] compared with other commercial materials (Acotec panel, EPS precast) and brick wall [6, 21, 22]. Acotec panel is a hollow concrete panel using sand, stone and portland cement [21]. Due to the high porosity and small thickness, the weight per m² of the wall panels is significantly lighter 20-30% than traditional brick walls, but super strength (over 25 MPa). EBS precast makes of expanded polystyrene concrete core material sandwiched between thin fiber cement or calcium silicate board [22]. This wall panels are very light with its density is only 750-800 kg/m³ and the weight of 100mm wall is 75 kg/m², equivalent to 1/2- 1/3 of the Acotec panel and clay-burn brick wall (BW). The panel products are highly resistant to moisture, sound insulation, heat insulation and fireproof. LGCP is as light as EPS panel, but its strength reaches 8.2 MPa and a quite low absorption coefficient (only 3.9%). These all wall panels are versatile and be well used as partition walls, external walls and even as floorings.

| No. | Properties                        | LGCP              | BW           | Acotec panel | EBS precast |
|-----|-----------------------------------|-------------------|--------------|--------------|-------------|
| 1   | Typical dimension, mm             | 2440x610x100      | 220x105x60   | 2440x610x100 | 2440x610x100 |
| 2   | Density, kg/m³                    | 900               | 1400-1900    | 1500-1800    | 750-800     |
| 3   | Surface density, kg/m²            | 81                | ≤200         | 140-160      | ≤75         |
| 4   | Heat transfer coefficient, W/m.K  | 0.22              | ≤1.0         | ≤0.5         | ≤0.5        |
| 5   | Compressive strength, MPa         | 8.2               | ≥5.0         | ≥25.0        | ≥3.5        |
| 6   | Water absorption, %               | 3.9               | ≤16          | ≤8.0         | ≤8          |

2.2. Assessment methods

Technical effectiveness of LGCP in multi-story and high-rise buildings has calculated by the reduction of dead load and construction cost of the LGCP wall compared to that used CB.

To evaluate the environmental efficiency, the two criteria are total CO₂ emissions and energy consumption during the production of materials and wall construction is calculated and compared. In
this research, the production and construction phase constitute the boundaries of the system. The motivation for this choice was our awareness that the production phase is the most relevant in terms of environmental impacts, as demonstrated by several authors [23-25]. The production phase includes the processing of raw materials, transportation, and the production of geopolymer concrete or cement mortar and also for mixing. Figure 1 shows the boundaries of the LGCP wall system. Table 2 shows the gathered data for energy and CO$_2$ release from manufacturing and construction [3, 6, 23-25].

![Figure 1. Boundaries of the LGCP wall system.](image)

| Type of material                        | CO$_2$ emission, $e_{\text{co}_2}$ (kg/t) | Embodied Energy, ee (kJ/t) |
|----------------------------------------|------------------------------------------|---------------------------|
| Portland Cement                        | 865                                      | 4920                      |
| Fly ash (FA)                           | 197                                      | 2414                      |
| GGBS                                   | 143                                      | 1747                      |
| Sand                                   | 892                                      | 9819                      |
| Expanded polystyrene (EPS)             | 2550                                     | 88600                     |
| Water reducing agent                   | 736                                      | 3500                      |
| NaOH solution                          | 920                                      | 4470                      |
| RHA solution                           | 520                                      | 1430                      |
| CB wall construction                   | 129                                      | 247                       |
| LGCP wall construction                 | 89                                       | 953                       |

3. Results and discussion

3.1. Technical analysis
The technical efficiency of using LGCP in research projects is assessed primarily by comparing the total dead load of brick wall structure compared to that of the LGCP wall. Brick wall (BW) has a thickness of 120mm. It is composed of hollow brick 220x100x60mm, cement mortar, and plastering thickness is 20mm. LGCP wall only has LGCP with 90mm thick and 5mm connecting grout. The dead load of the wall structure is determined by the formula (1):

$$q = (k \cdot \gamma \cdot \frac{d}{1000}) \cdot h$$  \hspace{1cm} (1)

With $k$ is the confidence factor; take by 1.1 for hollow bricks and LGCP or by 1.3 for mortar, plastering and connecting grout; $\gamma$ is the bulk density of the materials; take 1400 kg/m$^3$ for hollow bricks; 2000 kg/m$^3$ for mortar; 900 kg/m$^3$ for LGCP and 1800 kg/m$^3$ for connecting grout.
δ and h: is the layer thickness of the material (mm) and the design height of the wall (m).
The dead-load of BW and LGCP wall is 258 kG/m$^2$ and 111 kG/m$^2$. When the height wall or partition is h=3.1m, the distributed dead load value of BW and LGCP wall are respectively 800 kG/m and 343 kG/m. Therefore it can be seen that with the same meter length, the LGCP wall is 57% lighter than brick walls.

According to the national specifications on building partition, a 90mm wall can replace traditional 120mm, and the thickness after plastering is 85mm less, that is the usable area of 1m$^2$ can be increased for each extension of 11.8m with an increased of the utilization rate of 4-6%. So the usable area of 4.26m$^2$ can be encreased for every house of 100m$^2$, and the value of the increased usable area is higher than the wall cost. Therefore, the LGCP wall is very suitable for the partition or splitting of the shop and apartment [6, 21, 22]. Also, the LGCP construction will be simpler and shorten the construction time (from 3-4 times higher than BWs), saving labor costs for not having to plaster and just need to paint directly on the wall or use wallpaper (Figure 2).

![Image](image_url)

**Figure 2.** Construction site uses Brick (left) and LGCP (right) [21].

### 3.2. Cost analysis

Economic efficiency is assessed by comparing the total cost of transporting, purchasing materials and constructing for the two options of the one square-meter of BW and LGCP wall (Table 3). The materials costs are based on the published price of construction materials in Hanoi city-Vietnam. Table 3 reports the cost data of the masonry structures. Due to the LGCP is very light, easy assembly so the transportation cost decreases significantly (about 84%). It also needs the low labors directly engaged in construction and installation. These lead to the construction costs decrease up to 94% compared to these costs of a BW. However, the LGCP price is quite high, up to 180,000 VND/m$^2$, so the total cost of buying materials for brick walls is 65% lower than that of LGCP walls. Therefore, the total cost for the LGCP wall is still reduced by about 42% compared to the brick wall.

| Cost items          | Brick wall | LGCP wall |
|---------------------|------------|-----------|
| Transport cost      | 18,176     | 6,811     |
| Brick (VND)         | 8,843      | 6,713     |
| Type of transport vehicle | Trailer truck | Trailer truck |
| Weight (T)          | 32         | 32        |
| Unit price (VND)    | 2,652,000  | 2,652,000 |
| Mortar (VND)        | 9,333      | 98        |
| Type of transport vehicle | mixer truck | truck |
| Capacity (m3 or T)  | 7.5        | 32.0      |
| Unit price (VND)    | 1,400,000  | 2,500,000 |
| Purchasing cost     | 115,250    | 181,001   |
| Brick (VND)         | 68,750     | 180,000   |
| Quantity            | 55         | 1         |
| Unit price (VND)    | 1,250      | 180,000   |
| Mortar (VND)        | 46,500     | 1,001     |
| Mortar volume (m3)  | 0.050      | 0.001     |
| Unit price (VND)    | 930,000    | 1,430,000 |
### 3.3. Environmental assessment

For a preliminary assessment of environmental performance, the research identified two factors that have a great impact on the environment as CO\textsubscript{2} emissions and energy consumption during LGCP and mortar manufacturing, LGCP and brick wall construction. Calculation results of CO\textsubscript{2} emission (Eco\textsubscript{2}) and embodied energy (EE) of 1m\textsuperscript{3} cement mortar, cement grout, and geopolymer concrete are shown in Table 4 [3, 5, 6].

| Type of material          | Quantity, kg/m\textsuperscript{3} | Eco\textsubscript{2}, kg | EE, kJ |
|---------------------------|------------------------------------|--------------------------|--------|
| Cement mortar             | 1601                               | 27386                    |        |
| Portland Cement           | 320                                 | 277                      | 1574   |
| Sand                      | 1484                                | 1324                     | 14572  |
| Mixing and production     | 1                                   | 0.065                    | 11240  |
| Cement grout              | 1                                   | 1624                     | 27095  |
| Geopolymer concrete       | 257                                 | 17744                    |        |
| Fly ash (FA)              | 403                                 | 79                       | 973    |
| GGBS                      | 269                                 | 38                       | 470    |
| Expanded polystyrene (EPS)| 10.5                                | 27                       | 930    |
| Water reducing agent      | 4.5                                 | 3                        | 16     |
| NaOH solution             | 28                                  | 26                       | 125    |
| RHA solution              | 161                                 | 84                       | 230    |
| Mixing and production     | 1                                   | 0.07                     | 15000  |

The amount of CO\textsubscript{2} emissions of BW or LGCP wall is calculated by the total amount of CO\textsubscript{2} generated from the production of brick, LGCP, cement mortars, cement grout for LGCP connecting and wall construction process. Table 5 reports the environmental efficiency of using the LGCP wall compare to a brick wall. The results show that the use of a geopolymer concrete mixture to make the LGCP wall has a much better environmental efficiency than the usage of clay-burn brick walls. CO\textsubscript{2} emissions from production phrase and construction phrase only is 224 kg/m\textsuperscript{2} and 89 kg/m\textsuperscript{2} corresponding to decrease by 73% and 31% compared to the brick production. This leads to a reduction of 48% of the total CO\textsubscript{2} generated when using LGCP. Despite the energy consumption in LGCP construction is 3.9 times higher than that of brick, but the total energy consumption of LGCP wall still reduces by 17 times due to LGCP energy consumption in the production phase is very small, only 1616 kJ/m\textsuperscript{2}.

| Items                    | Eco\textsubscript{2}, kg | EE, kJ |
|--------------------------|--------------------------|--------|
|                          | Brick wall | LGCP wall | Brick wall | LGCP wall |
| Production phrase        | 90          | 224       | 44874      | 1616      |
| Brick or LGCP production | 10          | 23        | 43505      | 1597      |
| Mortar or grout production | 80       | 1         | 1369       | 11        |
| Construction phrase      | 129         | 89        | 247        | 953       |
| Total                    | 219         | 113       | 45121      | 2569      |
4. Conclusions
This study highlights that the use of industrial waste such as Fly ash, Ground granulated blast furnace slag and agricultural waste (rice husk ash) based on lightweight geopolymer concrete for making LGCP will address sustainability issues such as the resource conservation and conversion of by-products to useful and valuable products.
The use of lightweight geopolymer concrete panels as the wall in high-rise buildings is bringing high economic-technical-environmental benefits compared to clay brick walls. Specifically: reducing over 57% weight load of wall structure, saving more than 42% in material costs; reduce over 48% CO2 footprint and up to 17 times energy consumption from producing and construction compared to those hollow clay brick.

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