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# Evaluation of Carbon Emission Reduction in Concrete Using Fly Ash and Slag: Case Studies from Vietnam

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**Abstract:** Concrete is one of the most widely used construction materials; however, its high cement content is a major contributor to global carbon emissions. This study applies Life Cycle Assessment (LCA) to evaluate carbon emissions from various cement replacement scenarios using fly ash and slag, based on multiple studies in Vietnam. Experimental results show that replacing 20%–40% of cement with fly ash reduces emissions by 9.14%–40%, while 40% slag replacement achieves a 31.84% reduction. A combined mix with 20% fly ash and 20% slag offers the best balance, reducing emissions by 32.16% while maintaining a compressive strength of approximately 50 MPa. These findings highlight the potential of industrial by-products in reducing carbon footprints while maintaining concrete performance. This study provides insights for optimizing sustainable concrete mix designs in Vietnam, promoting greener construction practices.

**Keywords:** Concrete material, Carbon emission, Carbon Inventory.

## 1. Introduction

The construction industry is a significant contributor to global carbon emissions. According to the World Energy Agency, the construction industry contributes up to 20% of global carbon emissions from energy consumption 5–10% in developed countries and 10–40% in developing countries [1]. In response to the global climate crisis, numerous international organizations such as the Intergovernmental Panel on Climate Change (IPCC), International Energy Agency (IEA), International Organization for Standardization (ISO), the United States Environmental Protection Agency (EPA), and the World Bank [2-4], along with several national governments (e.g., UK, US, Japan, South Korea, and China), have developed methods and online tools to support carbon emissions inventory and reduction strategies.

Initial efforts focused on improving raw material and energy efficiency, but comprehensive emissions studies in construction only gained traction after the 1990s, when early research was limited [5], [6] introduced a framework for estimating carbon footprints based on infrastructure needs and population growth. Recently, Life Cycle Assessment (LCA) has been widely used, with concrete emissions studies primarily relying on Process-LCA methods [7-14]. For example, Kim et al. [10] found that construction machinery can contribute 60–95% of emissions, while raw material extraction in concrete production accounts for nearly 90% of total emissions. Moreover, using alternative materials in concrete reinforcement can reduce waste by approximately 60% compared to conventional materials [13, 14].

In Vietnam, rapid economic growth, urbanization, and infrastructure development have made it one of the fastest-growing emitters of greenhouse gases. Although its per capita emissions are higher than those of other Southeast Asian countries, they remain lower than those of China and Japan [1]. This situation calls for robust emissions inventories and reduction strategies to support sustainable development. However, research on carbon emissions in Vietnam's construction sector is still limited.

The first official report on cement production emissions was released by the Ministry of Natural Resources and Environment, revealing that cement and thermal power plants emit an average of 0.85 tons of $CO_2$ per ton of clinker [15]. Further studies have inventoried emissions for building materials like brick and glass [16] and concrete [17]. Binh et al. [17] evaluated Ultra High-Performance Concrete (UHPC) with a compressive strength exceeding 120 MPa, incorporating fly-ash and silica fume as partial cement replacements. Their findings showed a 23.2% $CO_2$ reduction when fly ash content increased from 0% to 30%, a 44.3% reduction with a 30% increase in silica fume, and a 30.9% reduction when both were used (fly ash plus 10% silica fume). Nonetheless, emission inventories for other concrete types remain scarce, limiting the development of low-carbon construction models in Vietnam.

This paper aims to assess the effectiveness of reducing carbon emissions by replacing cement in concrete with fly ash and slag. To achieve this objective, the research process includes: (i) overviewing type of concrete using fly ash and slag, (ii) conducting an emissions inventory based on the LCA method and (iii) discussing optimal mix designs. The types of concrete were overviewed from the previous reseach, which focusing on the concrete using a portion of fly-ash and slag.

## 2. Methodology

### 2.1. LCA method for Concrete

Life Cycle Assessment (LCA) analyzes the environmental impact of a product or service throughout its life cycle, from raw material extraction to transportation, production, use, recycling, or disposal. Its structure, procedures, and requirements are detailed in ISO 14040:2006. For concrete, the life cycle in buildings includes four main phases: material production, construction, use and maintenance, and demolition [10], [18-20], as shown in Fig. 1. This study focuses on the material production phase, which involves three key emission-generating processes: raw material extraction and processing, transportation of raw materials, and concrete production (Fig. 2). The first stage includes processing cement, aggregates, water, and additives, with cement being the largest $CO_2$ emitter due to the burning of limestone and clay.

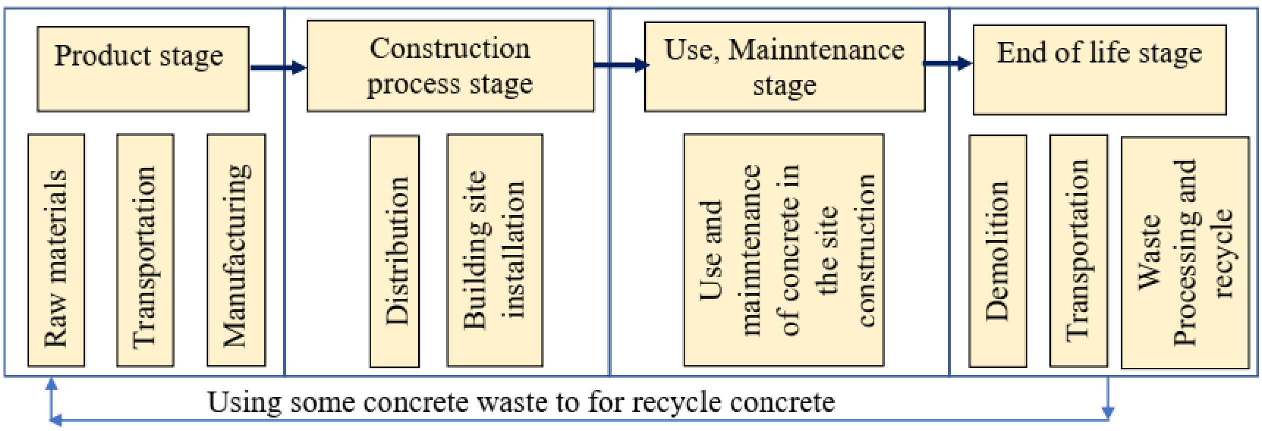



**Fig 1**. System Boundary for Concrete Life Cycle Assessment [11] [20]

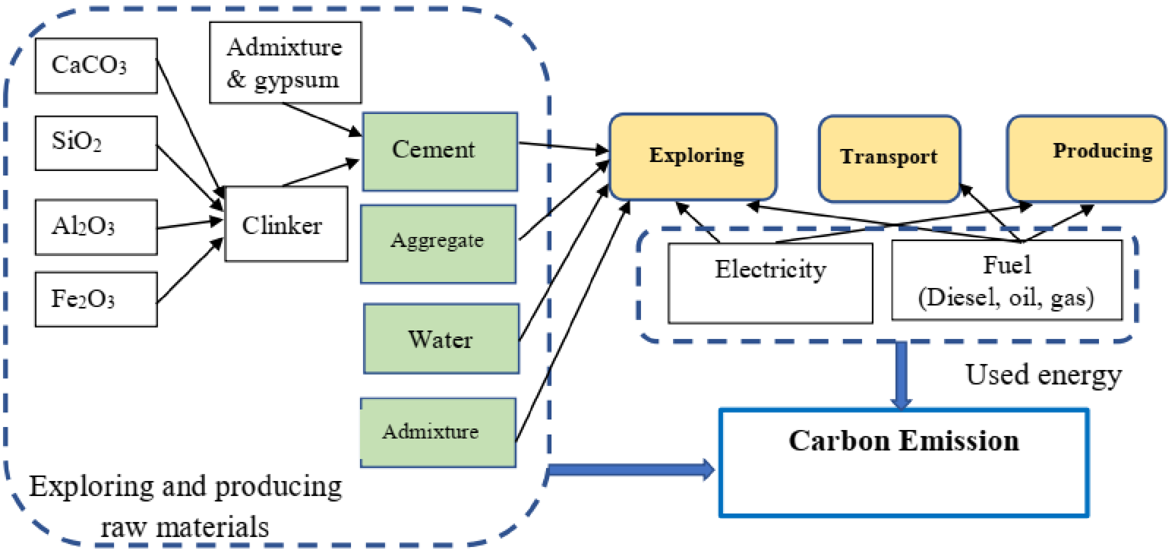



**Fig 2**. Concrete Production Process and Carbon Emission Sources [7]

**Table 1**. Emission sources from each activity of concrete

| Activities | | Emission sources | | |
|---|---|---|---|---|
| | | Direct | Indirect | Other Indirect |
| Material | Cement | Coal firing of kiln<br>On site fuel – vehicles<br>On site fuel – kiln start up<br>Calcination of raw materials | Electricity | Delivery of raw materials to site |
| | Fly ash | On site fuel – vehicles | Electricity | Delivery of raw materials to site |
| | Slag | On site fuel – vehicles | Electricity | Delivery of raw materials to site |
| | Aggregate | On site fuel – vehicles<br>Explosive | Electricity | Delivery of raw materials to site |
| | Admixtures | On site fuel – vehicles | Electricity | Delivery of raw materials to site |
| | Reinforcing | On site fuel – vehicles<br>On site fuel – furnace | Electricity | Delivery of raw materials to site |
| Producing | Precast products | Coal, gas firing of boilers for water heating | Electricity | Delivery of raw materials to site |
| | Ready-mix | On site fuel - loader | Electricity | Delivery of raw materials to site |
| Transportation | For raw-material | Fuel energy (diesel, oil, gas) | | |

The next process involves transporting raw materials from mining sites to production facilities. Finally, concrete production and casting require fuel (oil/gasoline) and electricity to power machinery, contributing further to carbon emissions. The carbon emission sources of materials are divided into three types as direct, indirect and other indirect with the main activities as shown in Table 1. According to these activities, the equations to calculate carbon emissions for each material and process are provided in the following sections.

### 2.2. Calculate the amount of carbon emissions

The total carbon emissions associated with concrete production are derived from three primary stages: raw material production, transportation, and concrete mixing and casting [10]. The emissions for each stage are estimated using the following equations:

(1) Emissions from Material Production:

$$CO_2M = \sum (M_i \times f_{(CO2)Mi}) \quad (1)$$

$CO_2M$ is the $CO_2$ emission quantity at the raw material stage of the production of a unit of concrete (kg-$CO_2$/$m^3$); M(i) is the amount of material used (kg/$m^3$) in the concrete; and the $f_{(CO2)Mi}$ is the $CO_2$ emission factor for each material (kg-$CO_2$/kg)

(2) $CO_2$ emission in transportation stage

$$CO_2T = \sum (M_i/L_t) \times (d/e) \times f(CO_2)_T \quad (2)$$

Here, $CO_2T$ is the quantity of $CO_2$ emitted during the transportation of a unit of produced concrete (kg-$CO_2$/$m^3$); M(i) is the amount of material used (kg/$m^3$) in the concrete; $L_t$ is the transportation load (tons); d is the transportation distance (km); e is the fuel efficiency (km/L); and $f(CO_2)_T$ is the $CO_2$ emission factor of the energy resource (kg-$CO_2$/kg).

(3) $CO_2$ emission from concrete mixing and casting:

The $CO_2$ emission in the manufacturing stage comes from using the energy for material testing by the requirement of concrete, for mixing the material and casting concrete into a cylindrical:

$$CO_2P = \sum (M_c \times f(CO_2)_P) \quad (3)$$

$CO_2P$ is the amount of $CO_2$ emitted during the concrete manufacturing stage for producing a unit of concrete (kg-$CO_2$/$m^3$); $M_c$ is the amount of concrete (kg/$m^3$), and $f(CO_2)_P$ is the $CO_2$ emission factor for mixing the material and casting concrete (kg-$CO_2$/kg).

Besides these processes, any processing that requires the use of energy, such as electricity or fuel, must also be calculated. $CO_2E$ denotes the $CO_2$ emissions from energy use, and $f(CO_2)E$ is the $CO_2$ emission factor of an energy resource (kg-$CO_2$/kg).

### 2.3. Determining the emission factors

The emission factor is crucial for $CO_2$ inventory processing. Equations (1)–(3) define emission factors for materials ($f(CO_2)Mi$), transportation ($f(CO_2)T$), mixing and casting ($f(CO_2)P$), and energy resources ($f(CO_2)E$).

**Table 2**. The Carbon emission factors in the reference sources

| Sources | **Materials** | **Units** | **ICE V3.0. (1)** | **EPA (2)** | **EU (3)** | **EU - GWP (4)** | **China (5)** | **Korea LCI DB (6)** | **Japan (7)** |
|---|---|---|---|---|---|---|---|---|---|
| Materials for Concrete Production | Cement, OPC | $kgCO_2$/kg cem./clinker | 0,912 | 0,959 | 0,938 | 0,898 | 0,82-1,162 | 9,44E-01 | 0,7666 |
| | Slag Cement | $kgCO_2$/kg | | | | | | 0,208 | 0,4587 |
| | Fly Ash, Class F Class B-Japan | $kgCO_2$/kg | 0,004 | 0,093 | | 0,004 | 0,0015 | | 0,624 |
| | Silica, Fume | $kgCO_2$/kg | | 0,014 | 7E-9 | | | 1,05 | 0,00774 |
| | Natural aggregate | $kgCO_2$/kg | 0,00747 | | 0,0001 | 0,029 | 0,003 | 7,06E-03 | 0,0029 |
| | Recycled aggregates | $kgCO_2$/kg | | | 0,00328 | 0,005 | | 1,49E-02 | 0,0177 |
| | Riverbed sand | kg $CO_2$/ $m^3$ | | | | 0,002 | 0,00164 | 0,00135 | |
| | Crushed sand | kg $CO^2$/ $m^3$ | | | | 0,005 | | 4,25E-03 | |
| | Water | $kgCO_2$/kg | 0,000344 | | | 0 | | 0,00131 0,000196 | |
| | Average Admixture | $kgCO_2$/kg | 1,88 | | | | 1,164 | | |
| | Plasticisers and Superplasticisers | $kgCO_2$/kg | 1,88 | | 0,88547 | 0,002 | 0,0007 | 0,25 | 0,0265 0,0196 |
| | $Na_2SiO_3$ | $kgCO_2$/kg | | | | | | 1.51E+00 | |
| | NaOH 50% | $kgCO_2$/kg | | | | | | 6.29E-01 | |

**Table 2.** (tiếp)

| Sources | Materials | Units | ICE V3.0. (1) | EPA (2) | EU (3) | EU - GWP (4) | China (5) | Korea LCI DB (6) | Japan (7) |
|---|---|---|---|---|---|---|---|---|---|
| Transportation and Energy | LCI for heavy trailer | $kgCO_2/tKm$ | | | 0,092 | | | | |
| | LCI for Medium-heavy trailer | $kgCO_2/tKm$ | | | 0,281 | | | | |
| | Truck (2.5) ton | $kgCO_2$/ton.km | | | | | | 1,46E-01 | |
| | Diesel for Production | $g\text{-}CO_2/MJ$ $kgCO_2$/Input | | | 3,5 | | | 6,82E-02 | |
| | Diesel for transport | $KgCO_2$/litter | | | | | | 2,9 | |
| | Electricity (production) | kg-$CO_2eq/kWh$ | | | 0,02823 | | | 4,95E-01 | |
| Concrete mixing | Concrete batching energy | $kgCO_2/kg$ | 0,0007 | | | | | | |
| | Concrete pre-casting | $kgCO_2/kg$ | 0,0142 | | | | | | 0,0077 |

Reference Sources (1) Craig[21]; (2) Environmental Protection Agency[2][3]; (3) Sjunnesson[22]; (4) Kurda et al.[23]; (5) Li et al.[24]; (6) Korea LCI DB [25], Kim et al.[11]; Kwon et al.[26]; (7) Kawai et al.[27]

Emission factors were primarily collected from international databases such as the IPCC, the IEA Green Concrete LCA Web Tool, and regional studies from China, Japan, and Korea. Because Vietnam-specific data are limited or unavailable for some materials, the selected values were cross-referenced and adjusted to reflect Vietnamese industrial practices and energy profiles. The rationale for each choice and its source is summarized in Table 2.

## 2.4. Building the carbon emission factors for cement in Vietnam

As shown in Table 1, cement has the most complex carbon emissions due to multiple sources, while other materials (fly ash, slag, aggregates, admixtures, and reinforcements) mainly emit carbon from electricity and fuel use. Some materials, such as chemicals and admixtures, are imported into Vietnam. Therefore, this paper focuses on determining the carbon emission factor for cement, which varies based on production technology, limestone quality, and clinker fraction. These factors will be considered when collecting data and calculating emissions across different cement companies.

Several methodologies exist for inventorying carbon emissions in cement production, including IPCC Guidelines [28] and World Bank Council methods (Initiative, 2005). The $CO_2$ emission factor for cement is determined using the LCA approach (Fig. 3), covering three main processes: (i) raw material extraction (limestone, iron oxide), (ii) calcination in kilns to produce clinker, and (iii) grinding clinker with admixtures.

In these processes, the direct emission is derived by calcination clinker:

$CaCO3 + heat \Rightarrow CaO + CO2$ [28] (4)

The equation (6) shows the $CO_2$ emission depends on the ratio of $CaO/CO_2$ capture by interaction and the total of CaO using in Clinker

$CO_{2clinker}$ = Production data x EF clinker (5)

Where: EF clinker = fraction CaO • (44.01 g/mole $CO_2$/56.08 g/mole CaO)

=> EF clinker = fraction CaO • 0.785

The CaO fraction represents the CaO content in clinker, which may vary due to resource differences. The IPCC Guidelines suggest two methods to determine the emission factor. This paper applies the Tier 2 method [28], which estimates the average lime concentration in clinker using cement production data for selected Vietnamese cement types.

For other materials, emission factors are typically determined using similar processes. However, due to limited production data, their emission factors are not calculated here. Since these materials contribute minimally to concrete emissions, their values are referenced from existing sources (Table 2).

In Vietnam, most research focuses on enhancing concrete properties such as compressive strength, waterproofing, fire resistance, reduced weight, and durability. In this paper, compressive strength is used as the key classification factor to assess the effectiveness of the concrete models in reducing the $CO_2$ emission.

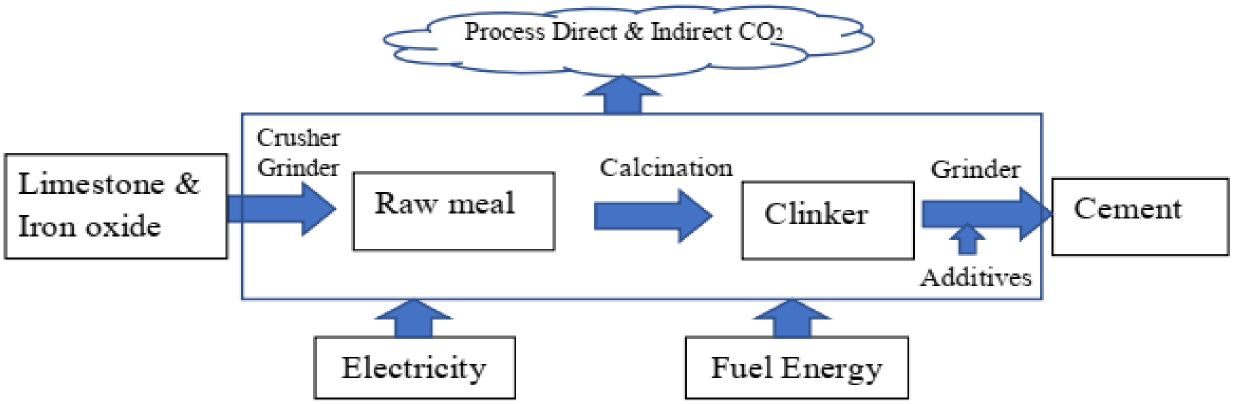



**Fig 3.** The processes of produced cement [28]

## 3. Results and discussion

### 3.1. Results of Emission Factor Determination

Three groups of emission factors were determined: materials, transportation, and concrete mixing. Tables 3 and 4 present the emission factors for materials, while Table 5 shows those for transportation and concrete mixing. Direct emissions come from clinker kilns, raw material reactions, and energy consumption for exploration, transportation, calcination, grinding, and cement production. Table 3 summarizes the carbon emission factors for selected cement types used in this study.

For other materials in concrete, emissions primarily result from energy and electricity use for extraction and grinding (aggregate, sand, fly ash, slag). Table 4 presents the emission factors for these materials, sourced from references listed in Table 1. The Korea LCI DB is the primary reference, developed according to ISO 14044 and is integrated with international LCA data networks, ensuring high transparency and reliability. These emission factors have been officially published and widely applied in LCA studies across Asia, particularly in the concrete production and precast industries, where similar technologies and energy systems are used. Given the technological similarities between South Korea, China, and Vietnam—especially in terms of cement and aggregate processing methods—the selected data are deemed appropriate proxies for the Vietnamese context.

**Table 3**. Carbon emission factor for some cements in Vietnam

| Cement types | Fraction of Clinker in cement (%) | Fraction of CaO in cement (%) | $CO_2$/CaO =44,01/56,08 | Carbon Emissions Factor of Cement from Elec. & Energy (kg$CO_2$/kg Cement) | Carbon Emissions Factor in Total (kg$CO_2$/kg Cement) |
|---|---|---|---|---|---|
| | A | B | C | D | E =AxBxC+D |
| But Son | 95 | 62.2 | 0.785 | 0.329 | 0.80175 |
| Song Gianh | 95 | 64.21 | 0.785 | 0.357 | 0.84534 |
| Nghi Son | 95 | 59.9 | 0.785 | 0.357 | 0.81256 |
| Hoang Thach | 95 | 64.6 | 0.785 | 0.357 | 0.74488 |
| Cam Pha | 95 | 65 | 0.785 | 0.357 | 0.85134 |
| Ha Tien | 95 | 62.57 | 0.785 | 0.357 | 0.73270 |
| Chinfon | 95 | 64.48 | 0.785 | 0.357 | 0.84739 |

**Table 4**. The emission factors for materials

| Materials | Units | EF $CO_2$ Value | Resources | |
|---|---|---|---|---|
| Slag Cement | $kgCO_2/kg$ | 0.0404118 | Calculating based on IPCC and ratio of Slag producted in Iron and Steel Prod. Vietnam factories | Iron and Steel Prod. Plants - IPCC (in China) |
| Fly Ash, Class F | $kgCO_2/kg$ | 0.0196 | Korea LCI DB | Korea LCI DB [25], Kim et al.[11]; Kwon et al.[26] |
| Silica, Fume | $kgCO_2/kg$ | 1.0500 | Korea LCI DB | |
| Natural Aggregate | $kgCO_2/kg$ | 0.0070625 | Korea LCI DB | |
| Recycled aggregates | $kgCO_2/kg$ | 0.0149 | Korea LCI DB | |
| Riverbed sand | $kgCO_2/kg$ | 9.64E-07 | Korea LCI DB | |
| Crushed sand | $kgCO_2/kg$ | 3.034E-06 | Korea LCI DB | |
| Water | $kgCO_2/kg$ | 0.000344 | ICE V3.0. | Craig[21] |
| Average Admixture | $kgCO_2/kg$ | 1.8800 | ICE V3.0. | |
| Plasticizers and superplasticizers | $kgCO_2/kg$ | 0.2500 | Korea LCI DB | Korea LCI DB [25], Kim et al.[11]; Kwon et al.[26] |
| $Na_2SiO_3$ | $kgCO_2/kg$ | 1.51E+00 | Korea LCI DB | |
| NaOH 50% | $kgCO_2/kg$ | 6.29E-01 | Korea LCI DB | |

**Table 5.** The emission factors for transportation, energy and mixing

| **Materials** | Units | **EF $CO_2$ Value** | **Resources** |
|---|---|---|---|
| **Transportation and Energy** | | | |
| LCI for heavy trailer | $kgCO_2/tKm$ | 0.0918 | EU |
| Truck Medium (5ton) | $kgCO_2/ton.km$ | 0.0812 | VN: 14l/100km |
| Diesel for Prod. | $g\text{-}CO_2/MJ$ $kgCO_2/Input$ | 0.0682 | Korea LCI DB |
| Diesel for transport | $kgCO_2/litter$ | 2.900 | Korea LCI DB |
| Electricity Prod. | $kg\text{-}CO_2eq/kWh$ | 0.6766 | Vietnam EVN (approval 19/3/2024) |
| **Concrete mixing** | | | |
| Concrete batching | $kgCO_2/kg$ | 0.00072 | ICE V3.0. |
| Concrete precasting | $kgCO_2/kg$ | 0.01419 | ICE V3.0. |

Additional sources such as ICE V3.0 and IPCC (based on China's data) are used for materials not covered in the Korea LCI DB. These sources are recognized internationally and widely used in regional carbon emission studies.

Table 5 provides emission factors for transportation and concrete mixing. In Vietnam, transportation emissions are referenced by the European Environment Agency and other international studies. Some research has published these reference values. This paper calculates emission factors based on total fuel consumption, vehicle types, and energy conversion to $CO_2$ equivalents, following IPCC and EEA methodologies.

### 3.2. Carbon Emission of Some Concrete Models

#### 3.2.1. Concrete Mix Models

In Vietnam, most concrete models focus on enhancing compressive strength by partially replacing conventional materials. The main approaches include (1) replacing cement with fly ash (F), (2) replacing cement with slag (S), and (3) combining fly ash and slag (FS). The replacement percentages are shown in Table 6. These models assess both compressive strength and slump. The most common concrete has a compressive strength of 30-50 MPa (ordinary-medium strength, OM). Some studies have also developed high-strength concrete (50-80 MPa, H) and ultra-high-performance concrete (up to 150 MPa, UH). This paper calculates the carbon emissions of these models to evaluate their environmental benefits. Table 7 categorizes the models based on material type (F, S, FS) and compressive strength (OM, H, UH).

**Table 6.** Concrete models overviewed from research in Vietnam

| Concrete Models | Compressive Strength | Percentage cement replaced | Name of concrete models | Research sources |
|---|---|---|---|---|
| 1. Replacing cement by fly ash (F) | 30-40MPa (OM) | 10 – 50% | F-OM1 | Lam et al. [30] |
| | | 10 – 40% | F-OM2 | Sykhampha et al. [31] |
| | | 20 – 60% | F-OM3 | Experiment |
| | 55-65 MPa (H) | 10 – 50% | F-H1 | Lam et al. [30] |
| | | 10 – 50% | F-H2 | Chanh et al. [32] |
| | 150 MPa (UH) | 10 – 30% | F-UH 90days | Thang et al. [33] |
| 2. Replacing cement by slag (S) | 30-40 MPa (OM) | 20 – 60% | S-OM1 | Experiment |
| 3. Replacing cement by mixing fly-ash and slag (FS) | 40-50 MPa (OM) | 20 – 40% | FS-OM2 | Experiment |
| | 50-80 MPa (H) | 100% | FS-H1 | Lam et al. [30] |

**Table 7.** The materials for mixing concrete in three models

| Models | Percentage of Cement reduced | Cement | Fly Ash, Class F | Natural Aggregate | Riverbed sand | Water | Admixture | Sources |
|---|---|---|---|---|---|---|---|---|
| *Unit* | *(%)* | *(kg)* | *(kg)* | *(kg)* | *(kg)* | *(kg)* | *(kg)* | |
| F-OM1 | 0 | 410 | 0 | 965 | 890 | 203 | 3,1 | Lam et al., [29]-[30] |
| | 10 | 369 | 41 | 965 | 890 | 203 | 3,1 | |
| | 20 | 328 | 82 | 965 | 890 | 203 | 3,1 | |
| | 30 | 287 | 123 | 965 | 890 | 203 | 3,1 | |
| | 40 | 247 | 164 | 965 | 890 | 203 | 3,1 | |
| F-OM2 | 0 | 380 | 0 | 1140 | 760 | 205 | 0 | Sykhampha et al. [31] |
| | 10 | 342 | 38 | 1140 | 760 | 205 | 0 | |
| | 20 | 304 | 76 | 1140 | 760 | 205 | 0 | |
| | 30 | 266 | 114 | 1140 | 760 | 205 | 0 | |
| | 40 | 228 | 152 | 1140 | 760 | 205 | 0 | |
| F-OM3 | 0 | 357 | 0 | 1062 | 829 | 178 | 1 | Experiment |
| | 20 | 287 | 71 | 1063 | 810 | 179 | 0,8 | |
| | 40 | 217 | 144 | 1070 | 795 | 181 | 0,6 | |
| | 62 | 146 | 220 | 1080 | 783 | 182 | 0 | |

**3.2.2. Change of carbon emissions by Fly ash replacing cement**

In the models using fly ash to replace cement in concrete [29-34], the fly ash was replaced by interval percentage as 10% or 20% and changed from 0% to 50%. Table 7 shows the material components of mixing concrete and Fig. 4a shows compressive strength responding to the content of fly ash increase in three models: F-OM1, F-OM2, and F-OM3

When replacing 10%–20% of cement with fly ash, the compressive strength initially increases but then decreases when the replacement level exceeds 20% in models F-OM1 and F-OM2 (Fig. 4a). In contrast, in F-OM3, the compressive strength decreases as the fly ash content increases. At 20% fly ash replacement, compressive strength increases slightly by 0.28%

and 2.17% in F-OM1 and F-OM2, respectively, but decreases by 15.57% in F-OM3; all values still meet the required standards. Carbon emissions decrease in all models with increasing fly ash content, with reductions of 9.14%, 16.65%, and 16.28% for F-OM1, F-OM2, and F-OM3, respectively, when 20% of cement is replaced by fly ash (Fig. 4b).

These results align with previous research on replacing cement with fly ash [35][36]. Sabău et al. [36] found that up to 25% of cement can be replaced with fly ash and emphasized the importance of considering transport distances to reduce carbon emissions. Han et al. [35] highlighted the impact of the water-to-binder ratio, noting that a higher fly ash content leads to a dilution effect, which helps lower CO2 emissions when the water-to-binder ratio is low.

Increasing both compressive strength and fly ash content contributes to reducing carbon emissions. Extending the maintenance period improves compressive strength, allowing fly ash replacement to reach 40% while still achieving the required strength of 45 MPa after 90 days. At this level of replacement, carbon emissions decrease by 32.47% compared to concrete without fly ash, as shown in Figs. 7 and 9. Increasing the maintenance time for concrete is an effective solution for increasing compressive strength and decreasing carbon emissions. In this model, carbon emissions were decreased dominantly by reducing the percentage of cement in material, especially cement. The carbon emissions by transportation and concrete mixing are 3-5%, respectively, and 9-10% compared with the total carbon emission of concrete.

Fig. 5 presents the results for high-compressive-strength concrete models (≥55 MPa) labeled F-H1 and F-H2. In both cases, the optimal fly ash replacement is up to 40%, achieving strengths above 55 MPa. At this level, carbon emissions decrease by 27.9% for F-H1 and 40.6% for F-H2. Although F-H1 and F-H2 have similar compressive strengths (Fig. 5a), F-H2 emits significantly more carbon due to its higher cement content (Fig. 5b). Additionally, transportation emissions for F-H2 (14%) are much higher than for F-H1 (3%). This comparison highlights the importance of carefully selecting materials to minimize cement usage and transportation distances, promoting using locally sourced materials in research and construction.

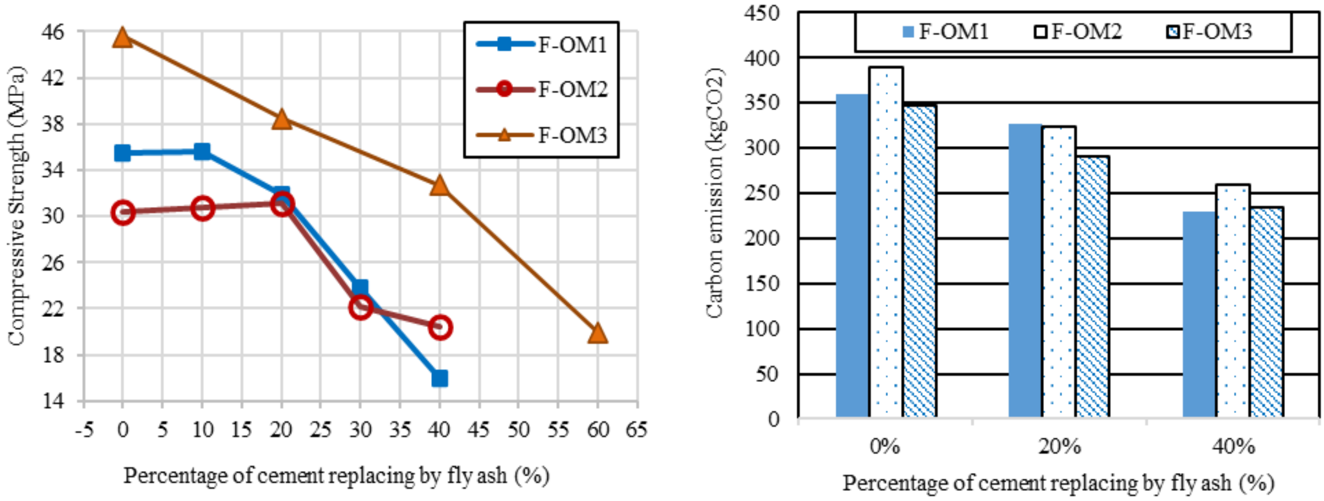
For ultra-high-performance concrete (UHPC), fly ash and silica fume (SF) improve strength and reduce cement usage. Fig. 6 shows the results for model F-UH with 0% and 10% SF, tested after 90 days of curing, with a target strength of 150 MPa. With 10% SF, compressive strength exceeds 150 MPa when fly ash replaces 10–30% of cement, with the highest strength observed at 20% fly ash replacement. In contrast, without SF (0%), the target strength is only reached at 20% fly ash replacement. $CO_2$ emissions decrease slightly with higher fly ash content - by only 1.42% without SF, but up to 7.74% with 10% SF. This demonstrates the potential of combining supplementary cementitious materials (SCMs) to achieve both high strength and environmental benefits. To achieve ultra-high strength, concrete must be cured at high temperatures (90±5°C) on the third and fourth days [33].

#### 3.2.3. Carbon Emission Reduction with Slag and Fly Ash

In Vietnam, slag is rarely used alone to replace cement, except in low-strength models like S-OM1 (Fig. 7). At 28 days, compressive strength decreases with increasing slag content (0–60%). However, at 90 days, strength remains stable, up to 40% slag replacement, reducing carbon emissions by 31.84%. Comparing 40% slag (S-OM1) and 40% fly ash (F-OM3) after 90 days, compressive strength reaches 53.5 MPa (S-OM1) and 45.5 MPa (F-OM3), while carbon emission reductions are similar (31.84% vs. 32.47%). Thus, slag replacement ensures higher strength while significantly cutting emissions.

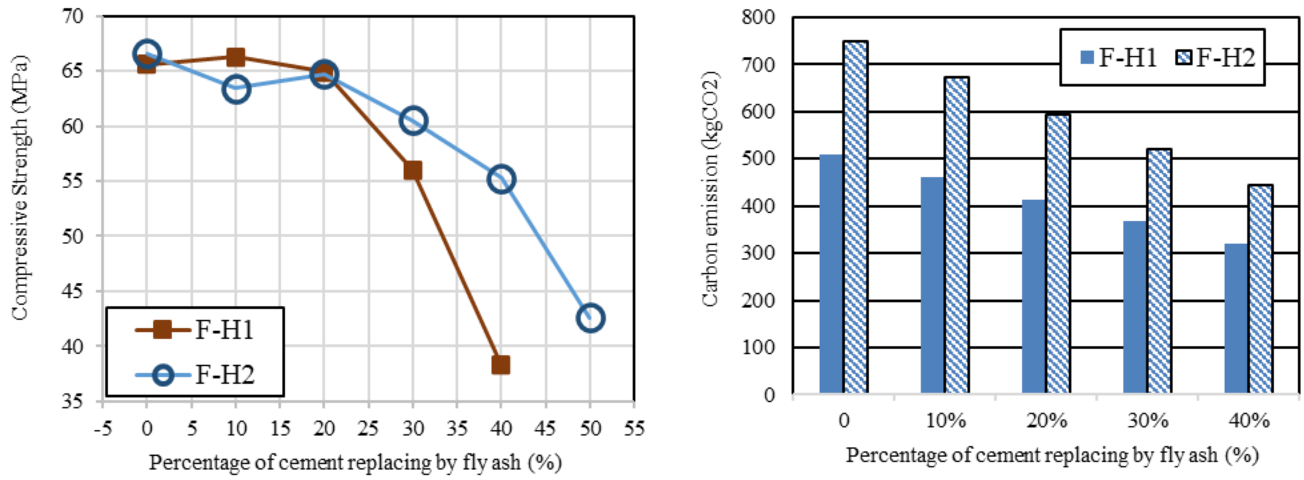
Fig. 8 presents the carbon emissions of concrete with varying levels of cement replacement using slag and fly ash. Four mix types were analyzed: S0.F0 (0% replacement), S2.F2 (20% slag, 20% fly ash), S2.F4 (20% slag, 40% fly ash), and S4.F2 (40% slag, 20% fly ash). This corresponds to cement replacement levels of 0%, 40%, and 60%, with the last two types differing in slag and fly ash proportions. The results indicate that compressive strength decreases as the replacement percentage increases, reaching its lowest value in S2.F4. However, the lowest carbon emissions occur in S4.F2, not in S2.F4. This suggests that a higher slag content in the replacement mix effectively reduces carbon emissions while maintaining better strength.

Fig. 9 compares compressive strength after 90 days for three cases: fly ash only (F-OM3), slag only (S-OM1), and a mix of both (FS-OM). With up to 40% replacement, S-OM1 and FS-OM achieve the required strength, comparable to 100% cement concrete. Slag replacement yields the highest strength, followed by the 20% slag–fly ash mix, while fly ash alone results in the lowest strength. Carbon emissions decrease similarly across all cases (Fig. 10). These findings highlight slag as the most effective replacement, with material selection depending on local availability. Slag and fly ash can fully replace cement. In model FS-H1, concrete is produced using only slag and fly ash in varying ratios (70/30 to 30/70), achieving high compressive strength (>60 MPa). Fig. 11 shows that higher slag content increases compressive strength (Fig. 11a) but also raises carbon emissions (Fig. 11b).



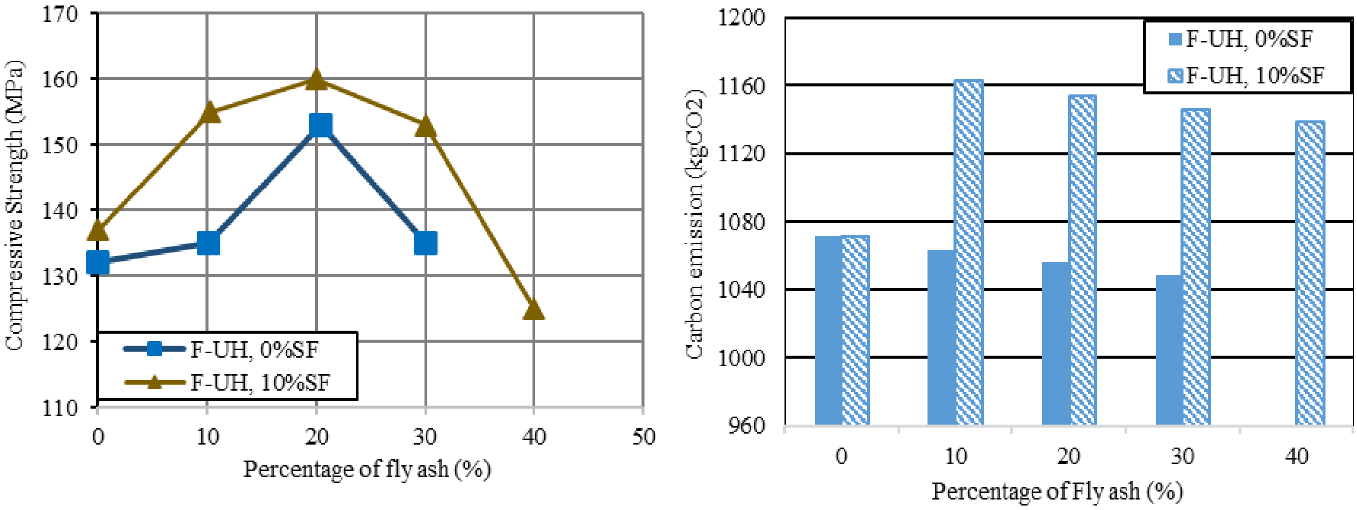

(a) (b)

**Fig 4**. The compressive strength (a) [29] and carbon emission (b) of OM concrete



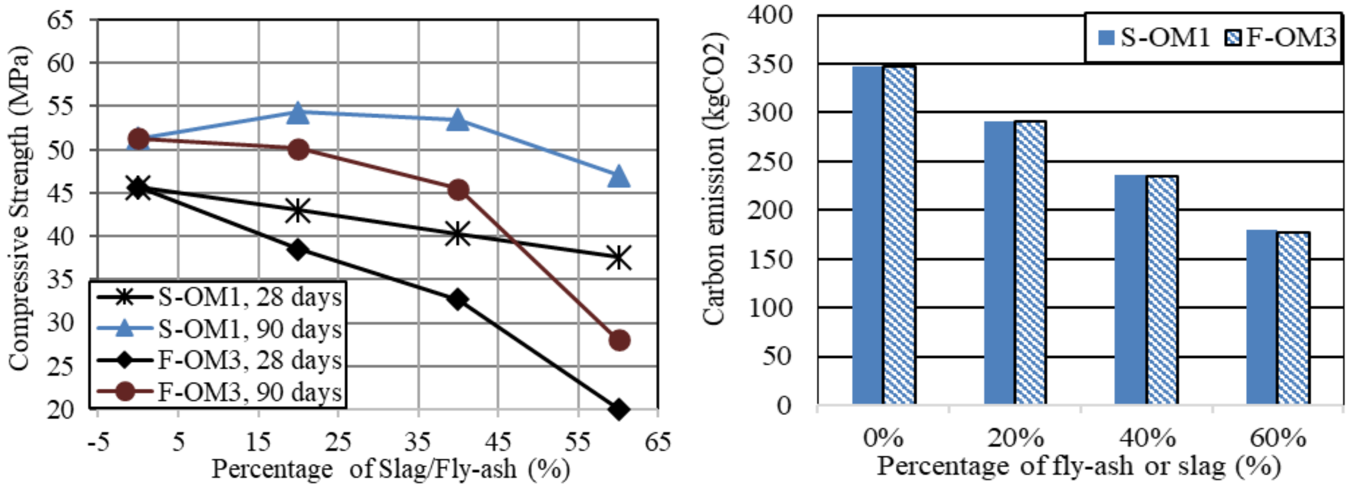

(a) (b)

**Fig 5.** The compressive strength (a) [32] and carbon emission (b) of High-Strength Concrete




(a) (b)

**Fig 6**. The compressive strength (a) [33] and carbon emission (b) of Ultra-High-Performance Concrete




(a) (b)

**Fig 7.** Effects of slag on the compressive strength (a) and carbon emission (b), OM concrere

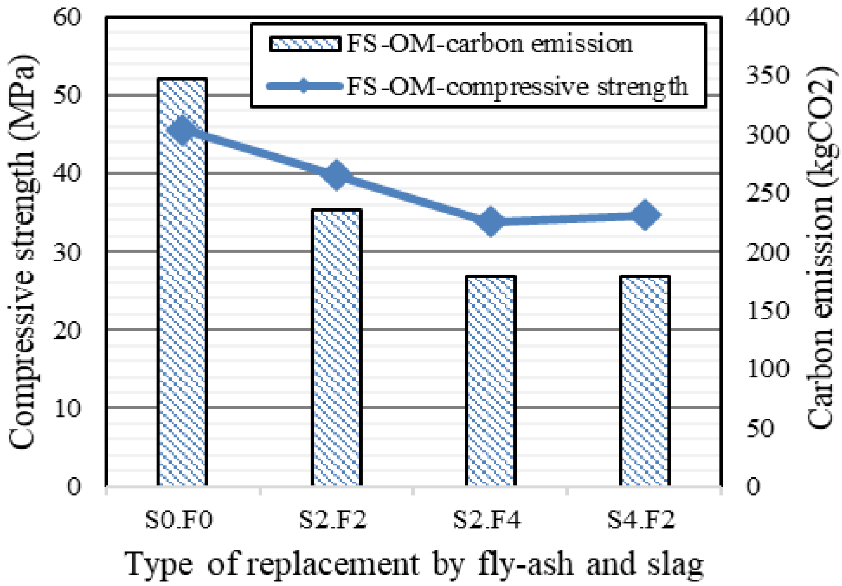



**Fig 8.** FS-OM Models

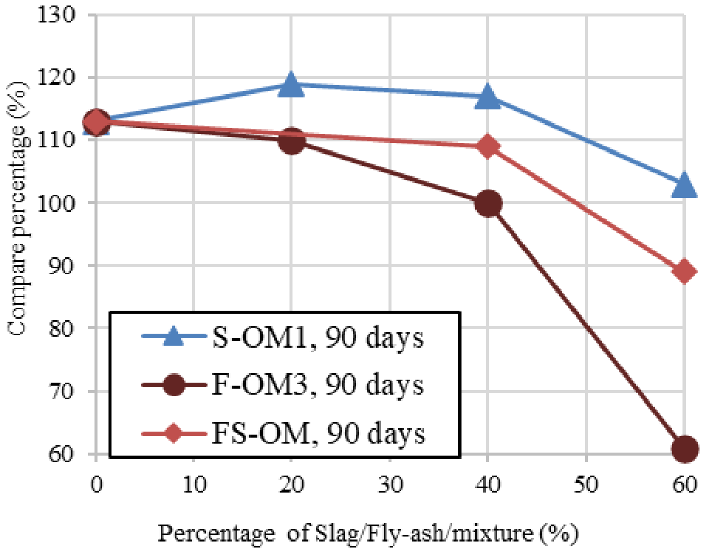



**Fig 9.** Comparison of compressive strength

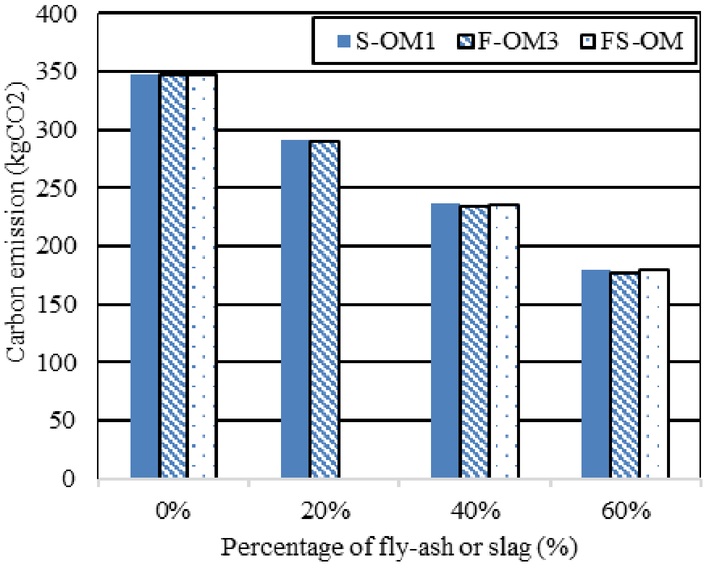
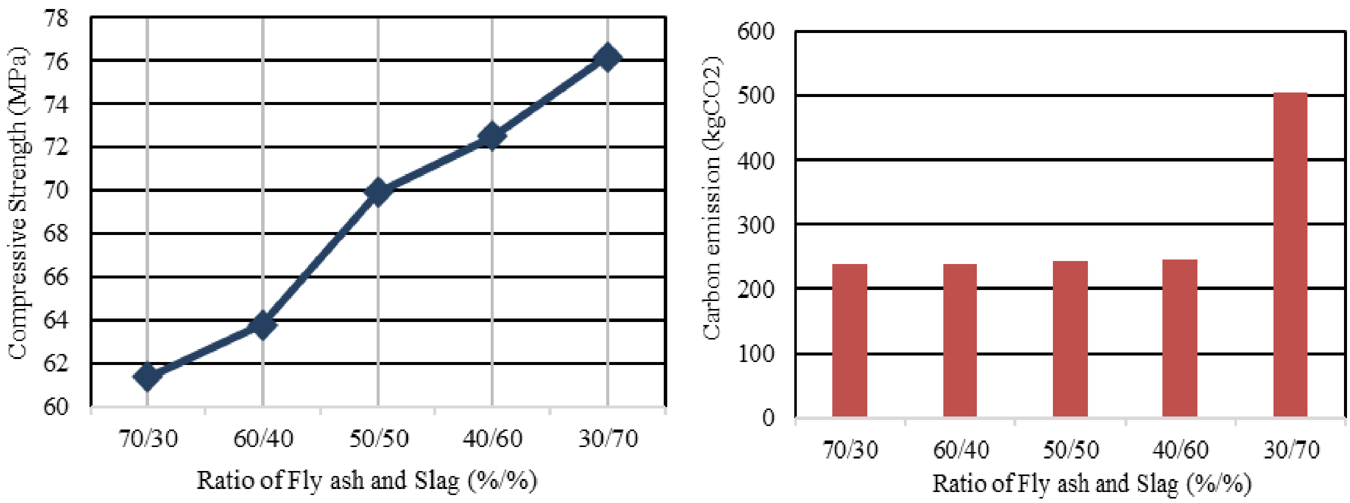
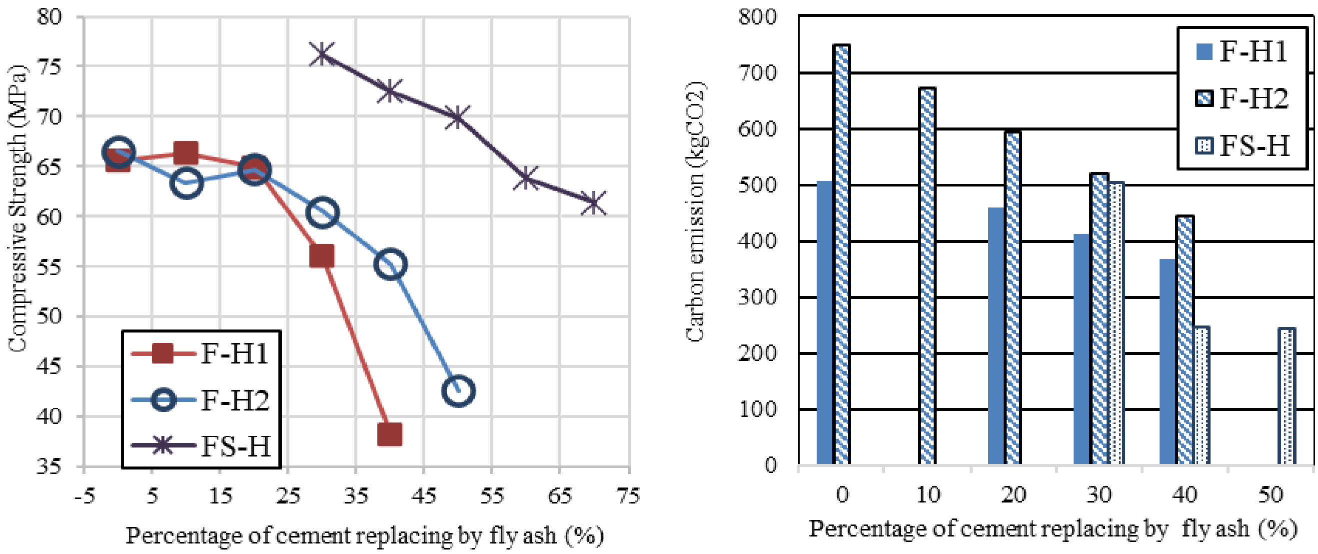



**Fig 10.** Comparison of carbon emission




(a) (b)

**Fig 11.** The compressive strenght (a) and the carbon emission (b) of FS-H1 model




(a) (b)

**Fig 12.** Effects of fly ash and slag on the compressive strength (a) and carbon emission (b)

Fig. 12a compares the results of models using only fly ash (F-H1 and F-H2) with the model using a combination of fly ash and slag (FS-H). Carbon emissions in FS-H range from 237 to 500 kg $CO_2$, which is lower than in F-H1 and F-H2 (366–799 kg $CO_2$). Based on these results, combining slag and fly ash should be considered as an effective strategy for reducing carbon emissions. In addition, high compressive strength can also be achieved by using a mix of fly ash and slag (Fig. 12b).

## 4. Discussion on Reducing Carbon Emissions in Concrete

Table 8 shows the results of carbon emission reduction for some calculated concrete types surveyed in Vietnam. The results are as follows:

When using only the fly ash, the optimum fly ash replacing cement is 20% in the case of OM-strength concrete. For H-strength concrete, the fly ash can be replaced up to 40% by extending the maintenance time of up to 90 days. Concrete with that optimum fly ash, the carbon emission reduces 9.14 – 16.28% in OM-strength concrete models and 27.9-40.6% in models of H-strength concrete. For model UH-strength, the optimal fly ash is 20%, replacing cement with a bit of 1.42 – 7.74%carbon emission.

When using only slag, the optimal replacement level is 40% in a model of OM-strength concrete, the carbon emission is reduced by about 31.84%

For combined use of fly ash and slag, the optimal mix consists of 20% fly ash, 20% slag, and 60% cement. This combination reduces the carbon emission by 32.16%. For the geo-polymer concrete, the mixing can replace 100% cement in concrete, and the carbon emission is less than 500 kg $CO_2$ for concrete samples by Vietnam standard as 40x40x160 mm, compared to 2123–2185 kg $CO_2$ for conventional cement-based concrete [33].

Based on the results summarized in Table 8, the FS-OM model (20% fly ash + 20% slag) demonstrates the best balance between carbon emission reduction (32.16%) and compressive strength (~50 MPa) among OM-strength concrete types. For high-strength concrete, F-H2 with 40% fly ash offers the highest $CO_2$ savings (40.6%), while FS-H1 achieves the highest strength (>60 MPa) with complete cement replacement. These models represent optimal choices for combining performance and environmental benefits.

Recent studies have advanced the development of low-carbon concrete by partially replacing cement with supplementary cementitious materials (SCMs) such as fly ash (FA) and ground granulated blast furnace slag (GGBFS). Research has shown that replacing 15–30% of cement with FA can meet strength and workability standards [36-37]. Combining FA with limestone has been found to reduce $CO_2$-eq emissions by 21.1% and increase compressive strength by 20.5% compared to limestone-only mixes [38]. A case study in Indonesia demonstrated that replacing 40% of cement with FA in FC 30 MPa concrete reduced emissions by 47% [39]. Additionally, recycling FA into lightweight aggregate has been identified as the most environmentally sustainable waste management option [40]. Other approaches, such as geopolymer concrete, carbon capture, and the use of recycled aggregates, can reduce $CO_2$ emissions by 30–50% while improving durability by 20–25% [41]. In Vietnam, the use of FA and slag aligns with global trends in sustainable construction. This study proposes replacing 40% of cement with FA and slag, achieving over 30% emission reduction—an effective and practical solution with lower impact compared to previous findings [39].

**Table 8.** Summary the effective of reducing carbon emission in models

| Concrete Model | Strength Class | Cement Replaced | Compressive Strength (MPa) | $CO_2$ Reduction (%) | Evaluation | Source Section |
|---|---|---|---|---|---|---|
| F-OM1<br>F-OM2<br>F-OM3 | OM | 20% FA<br>(Fly ash) | 31.9<br>31.1<br>38.5 | 9.14<br>16.65<br>16.28 | | 3.2.2 |
| F-OM3 | OM | 40 FA | 45.5<br>(90days) | 32.47 | | 3.2.3 |
| F-H1<br>F-H2 | H | 40% FA | >55 | 40.6 | Optimal in H group | 3.2.2 |
| F-UH | H | 20% FA<br>0% and 10% SF | 150 | 1.4 – 7.4 | | 3.2.2 |
| S-OM1 | OM | 40% Slag | 53.5 | 31.84 | Best strength in OM group | 3.2.3 |
| FS-OM | OM | 20% FA + 20% S | ~50 | 32.16 | Best balance | 3.2.3 |
| FS-H1 | H | 100% FA + S | >60 | <500 kg $CO_2$ | High strength, full replacement | 3.2.3 |

## 5. Conclusion

This paper reviews emission factors for calculating carbon emissions in concrete and determines emission factors for various types of cement in Vietnam. It also assesses carbon emissions in different concrete models, highlighting the current status of conventional and improved concrete.

Three concrete models are identified: ordinary-medium, high, and ultra-high compressive strength, with cement partially replaced by fly ash, slag, or a combination of both. The key findings include: Carbon emission factors for Vietnamese cement range from 0.821 to 0.867 kg $CO_2$/kg cement. Using fly ash and slag as partial replacements (20–40%) reduces carbon emissions by: 9.14–16.28% for ordinary-medium strength concrete, 27.9–40% for high-strength concrete, 1.42% for ultra-high-strength concrete. Replacing 40% of cement with slag reduces $CO_2$ emissions by 31.84%, while combining 20% fly ash and 20% slag (FS-OM model) achieves 32.16% reduction with ~50 MPa strength—making it the most balanced option for ordinary-medium strength concrete. In the high-strength category, F-H2 model (40% fly ash) provides the highest $CO_2$ savings (40.6%). Extending curing time and reducing transport distances are also effective strategies for further emission reduction

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