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Research Article

Embodied Carbon Impacts of Post-Earthquake Reconstruction in Reinforced Concrete Buildings: A Life-Cycle Assessment

Stela Sefa[1*], Eli Vyshka[1], Milidin Bakalli[2], Osman Metalla[1], Azem Hysa[2], Julian Sefa[3]

[1]Department of Engineering and Maritime Sciences, University Aleksander Moisiu Durres, Albania
[2]Department of Applied Sciences, University Aleksander Moisiu Durres, Albania
[3]Department of Environment, Polytechnic University of Tirana, Albania
***stelasefa@uamd.edu.al**

Abstract

This study quantifies the embodied carbon of structural concrete in post-earthquake residential reconstruction using a probabilistic life cycle assessment (LCA) framework. The analysis focuses on Durres, Albania, and addresses the lack of scalable, programme-level assessments. The methodology combines detailed structural inventory data with process-based LCA, Monte Carlo simulation (N = 10,000), and typology-based scaling. Emissions are estimated at the material and building levels and extrapolated to a reconstruction programme of 100 residential buildings. Sensitivity and statistical analyses are applied to identify key emission drivers and assess uncertainty. Results indicate a volume-weighted emission intensity of 0.325 t CO_2-eq/m^3, with cement contributing 80–85% of total emissions. Total programme emissions are approximately 2.15×10^5 tCO_2-eq. Scenario analysis shows that partial substitution of ordinary Portland cement can reduce emissions by 25–30%. The findings demonstrate that embodied carbon is primarily governed by cement content and structural design choices. The proposed framework enables programme-level assessment based on real structural data and supports the integration of LCA into early design stages for low-carbon reconstruction.

Keywords: Life Cycle Assessment; Embodied Carbon; Reinforced Concrete; Post-Earthquake Reconstruction; Monte Carlo Simulation; Cement Substitution; Programme-Level Assessment.

INTRODUCTION

The Mw 6.4 earthquake that struck Durres, Albania, on November 26, 2019, caused extensive damage to residential buildings and urban infrastructure, prompting a large-scale post-disaster reconstruction program [1, 2]. The event resulted in significant structural failures and human casualties. Official assessments indicate that nearly 95,000 structures across Albania sustained varying levels of damage [3]. More than 2,000 buildings were classified as structurally uninhabitable [4]. In the city of Durres alone, over 1,000 buildings were declared unfit for occupancy [3, 4]. As a consequence, demolition and reconstruction became unavoidable, primarily involving multi-storey reinforced concrete structural systems [3-5]. Table 1 summarizes the distribution of buildings by damage state (DS) following the 2019 earthquake in Durres.

Table 1 Number of buildings affected by the 2019 earthquake in Durres, Albania, by damage state (DS) [3, 4]

Damage State (DS)	Description	Number of buildings
DS1	Slight damage	42,000.0
DS2	Moderate damage	
DS3	Substantial damage	
DS4	Severe damage	492
DS5	Collapse	971

Post-earthquake reconstruction aims to restore structural safety and housing capacity, but it also leads to intensive material use, principally reinforced concrete [6]. Higher safety margins, increased reinforcement ratios, and stricter design requirements further raise material consumption [7]. This results in higher carbon embodied [6]. Concrete is a carbon-intensive material, primarily due to the production of cement [6, 8], which significantly contributes to greenhouse gas emissions [7, 9].

Despite the scale of reconstruction, the embodied carbon of post-disaster rebuilding in Albania has not been systematically quantified within a data-driven life-cycle assessment framework [10-12]. Existing studies mainly focus on material-level analyses or on single-building case studies [8, 13, 14] and rarely link detailed structural data with programme-scale estimation [13, 15]. As a result, the environmental impact of large-scale reconstruction remains insufficiently understood [10, 11, 16]. In particular, the contribution of structural concrete to total emissions is not well quantified at the level of building typologies and aggregated urban-scale impacts [13, 15]. The reconstruction programme in Durres provides a suitable case for this analysis. Standardized structural typologies, materials, and construction practices characterize it. This allows consistent comparison across multiple buildings and supports scaling of results.

This study applies life cycle assessment (LCA) to quantify the embodied carbon of structural concrete used in post-earthquake residential reconstruction in Albania [13, 17]. It focuses on reinforced concrete buildings constructed under a standardized national programme. It evaluates material-related CO_2 emissions at the structural level. It also identifies the main emission drivers within concrete production [8, 9]. The results are further extrapolated to a broader reconstruction stock. The proposed approach links material quantities, concrete mix design, and structural requirements. This enables the evaluation of emission reduction strategies at early design stages without compromising structural safety or seismic performance [8, 15, 19]. The study advances current knowledge by introducing a data-driven LCA framework that integrates detailed structural data with typology-based scaling. This approach enables the estimation of embodied carbon beyond individual buildings. Previous studies lack three key elements: (i) integration of real structural data with LCA modelling; (ii) scalable approaches for estimating emissions at programme level; and (iii) quantitative evaluation of key emission drivers under standardized design conditions. These limitations are addressed through an inventory-based and typology-driven framework. The approach supports both building-level and programme-scale assessment [20].

LITERATURE REVIEW

Concrete remains the dominant construction material in post-earthquake reconstruction due to its mechanical performance, durability, and widespread availability [9]. However, its production is associated with significant greenhouse gas (GHG) emissions, primarily driven by the embodied carbon of ordinary Portland cement (OPC) [9, 13]. Cement production alone accounts for approximately 5–8% of global anthropogenic CO_2 emissions [13, 14, 18]. The large volume of concrete used further amplifies its environmental impact [9]. Environmental Product Declarations (EPDs) under EN 15804 and databases such as the Inventory of Carbon and Energy (ICE) provide reference values for the embodied carbon of concrete [21, 22]. Reported intensities typically range between 250 and 400 kg CO_2-eq/m^3, depending on cement content and system boundaries [14, 21, 22]. These values are widely used as benchmarks in life cycle assessment (LCA) studies of concrete [14]. Table 2 summarizes representative embodied carbon values for reinforced concrete by strength class based on ICE databases, EPD datasets, and recent literature [8, 13, 14, 21, 22].

Table 2 Benchmark embodied carbon values for reinforced concrete by strength class under A1–A3 system boundaries

Source	Concrete Class	Median (kg CO_2-eq/m^3)	Range (kg CO_2-eq/m^3)	Notes
ICE database [22]	C20/25	~270	220–320	Lower cement content
ICE database [22]	C25/30	~300	250–350	Typical structural concrete
ICE database [22]	C30/37	~330	280–400	Higher cement demand
EPD datasets (EN 15804) [21].	C20/25–C30/37	~280–320	250–400	Aggregated values across strength classes; variability depends on clinker ratio
Literature (meta-studies) [8, 13, 14]	General RC	~300	250–350	Indicative values reported in LCA studies

As shown in Table 2, embodied carbon values for reinforced concrete under cradle-to-gate system boundaries (A1–A3) typically range between 250 and 400 kg CO_2-eq/m^3. Median values are generally in the range of 280–320 kg CO_2-eq/m^3, depending on concrete strength class and cement content. Higher-strength classes (e.g., C30/37) exhibit increased emissions due to higher cement demand. However, considerable variability exists across datasets, reflecting differences in clinker ratio, mix design, and data sources (ICE vs EPD) [21]. This variability introduces uncertainty in cross-study comparisons and highlights the need for consistent methodological assumptions [13, 15]. It also indicates that benchmark values alone are not sufficient to capture the structural and programme-scale characteristics of post-earthquake reconstruction [13, 15].

The embodied carbon of concrete is largely determined by its cement content, with ordinary Portland cement (OPC) identified as the primary emission source [6]. Cement production is a carbon-intensive process, with emission factors typically in the range of 0.8–0.9 t CO_2 per ton of cement, mainly due to clinker calcination and energy use [6, 18]. As a result, cement can account for approximately 85–90% of the total emissions associated with one cubic meter of conventional concrete [14]. Habert et al. emphasize that reducing the carbon footprint of concrete, therefore, requires both material-level interventions, such as clinker substitution, and system-level changes in production and design [8]. Given this dominant contribution, accurate quantification of cement-related emissions is critical in life-cycle assessment (LCA) studies of reinforced concrete structures, particularly in material-intensive contexts such as post-earthquake reconstruction [8].

In the Albanian context, the construction sector represents a significant source of greenhouse gas (GHG) emissions due to its reliance on energy-intensive materials and processes, particularly cement-based products [23, 24]. According to the National Greenhouse Gas Inventory Report [24], carbon dioxide accounts for roughly 66% of total greenhouse gas emissions, followed by methane (23%) and nitrous oxide (11%) [24]. Sectoral data indicate that cement production contributes around 12% of total CO_2 emissions, while manufacturing industries, including construction-related activities, account for approximately 25% [24]. Within the concrete production chain, Portland cement remains the dominant source of embodied carbon [18]. These figures confirm the central role of cement and construction materials in Albania's emissions profile and underline the need for context-specific assessment [10]. However, embodied carbon in post-earthquake reconstruction has not been systematically quantified [13, 15]. This gap is particularly relevant in Albania, where large-scale reconstruction programmes have been implemented following the 2019 earthquake, primarily using standardized reinforced concrete solutions [10-12]. Most existing studies on embodied carbon in concrete focus on conventional construction scenarios or material-level assessments [10-12]. LCA applications are typically based on standardized datasets, such as EPDs under EN 15804, or on single-building case studies under steady construction conditions [8, 14, 22]. As a result, they do not adequately capture the specific conditions of post-earthquake reconstruction, including large-scale material deployment and standardized structural typologies [16, 25].

Post-earthquake reconstruction programmes involve distinct characteristics, including accelerated construction timelines, standardized reinforced concrete typologies, and large-scale material deployment [10-12]. These conditions are not adequately captured in existing LCA studies. As a result, embodied carbon at the structural level remains insufficiently quantified in post-disaster urban reconstruction contexts [16, 25]. It should be noted that comparisons across datasets require consistent system boundaries and impact assessment methods (e.g., A1–A3 vs A1–A5 and EF 3.1 vs IPCC), as differences in methodological assumptions may lead to non-comparable results [14, 21]. Table 3 presents a comparative state-of-the-art (SOTA) analysis of life cycle assessment studies on embodied carbon in reinforced concrete. The comparison evaluates studies in terms of scale, data and methodological approach, uncertainty treatment, and reported findings and limitations.

Table 3 Comparative SOTA analysis of LCA studies on embodied carbon in reinforced concrete

Ref.	Context	Scale of analysis	Dataset size	Methodology	Uncertainty treatment	SCM analysis	Key findings	Main limitations
[8]	Global concrete	Material level	Not specified	Literature/ analytical	Not explicitly treated	Yes	Cement contributes ~85–90% of emissions	No building-level modelling
[14]	EPD-based dataset (global)	Material level	Large EPD datasets	EN 15804 database	Implicit (dataset variability)	No	250–400 kg CO_2-eq/m³ depending on mix	No real project data; no structural context
[25]	Post-earthquake reconstruction	Building level	Limited case study	LCA case study	Limited	Yes	270–340 kg CO_2-eq/m³; SCM reduces emissions	No scalability; no typology modelling
[26]	Post-earthquake reconstruction	Building level	Single case	Scenario-based LCA	No explicit	No	>360 kg CO_2-eq/m³ for OPC mixes	No uncertainty; no scaling
[13]	High-rise building	Building level	Single building	Process-based LCA	Sensitivity analysis	Yes	Identifies key emission drivers	No programme-scale extrapolation
[27]	Sustainable concrete materials	Material level	Laboratory/	LCA of mix design	Sensitivity analysis	Yes	SCM reduces	No building application

			mix-based				embodied carbon	
[15]	Urban metabolism	Urban scale	Conceptual/ aggregated	LCA+ urban modelling	Not explicit	No	Framework scaling emissions	No structural data integration
[16]	Post-disaster reconstruction	Urban/ policy level	Case - based	Quantitative + LCA concepts	Not explicit	No	Highlights scale of reconstruction impact	No quantitative structural modelling
Our Case	Post-earthquake reconstruction	Material + building + programme scale	2 buildings + scaling to 100	Process-based + probabilistic LCA	Explicit (Monte Carlo, N= 10,000)	Yes (15-30%)	0.325 t CO_2-eq/m^3; 2,15x10^5 t $CO_{2\text{-eq}}$ (programme)	Limited number of case study buildings

The comparison presented in Table 3 highlights that most existing studies are limited to material-level or single-building analyses. While several works identify cement as the dominant emission source and evaluate SCM substitution strategies [8, 13, 27-31], they do not address the scale and structural characteristics of post-earthquake reconstruction. In particular, uncertainty is often treated implicitly or not considered, and few studies provide probabilistic results [32-40]. Moreover, approaches that extend results beyond individual buildings are typically conceptual and lack integration with detailed structural data [15, 16]. In contrast, the present study combines three elements that are rarely addressed simultaneously: (i) material quantification based on real structural documentation, (ii) probabilistic life cycle assessment with explicit uncertainty propagation, and (iii) typology-based scaling to programme level. This positions the study between detailed building-level LCA and urban-scale assessments, providing a consistent framework for evaluating embodied carbon in large-scale reconstruction contexts.

RESEARCH GAP, SCIENTIFIC CONTRIBUTION, AND HYPOTHESES

Existing life cycle assessment (LCA) studies on reinforced concrete primarily focus on material-level analyses or single-building case studies under cradle-to-gate (A1–A3) system boundaries [13, 26, 27]. While these approaches provide benchmark values for embodied carbon intensity, they do not capture the structural complexity and scale of post-earthquake reconstruction [15, 25]. Three main limitations can be identified. First, most studies do not integrate detailed structural inventories into LCA modelling, relying instead on generalized datasets or simplified assumptions regarding material quantities [15]. Second, scalable methods for extrapolating building-level results to programme or urban scale remain limited, particularly in post-disaster contexts characterized by standardized construction practices [16, 25]. Third, comparisons with state-of-the-art benchmarks, such as Environmental Product Declarations (EPDs) and embodied carbon databases (e.g., ICE), are often inconsistent due to differences in system boundaries and modelling assumptions [14, 21, 22]. These limitations are particularly relevant in post-earthquake reconstruction, where large numbers of buildings are constructed under similar structural typologies and design constraints [16, 25]. As a result, current LCA methodologies do not provide structurally grounded and scalable estimates of embodied carbon [13, 15].

This study addresses these gaps through an integrated LCA framework tailored to post-earthquake reconstruction. The main contributions are: (i) Integration of structural inventory into LCA modelling, using detailed material quantities derived from construction documentation and validated through field data, improving the representativeness of embodied carbon estimates [13, 15]; (ii) Development of a typology-based scaling approach, for programme-level estimation [15, 29]; (iii) Quantification of embodied carbon at programme scale, providing an order-of-magnitude assessment of reconstruction emissions [16, 25]; (iv) Identification of dominant emission drivers, with emphasis on cement-related emissions [6, 8, 9, 18]; (v) Evaluation of mitigation strategies, based on substitution of OPC with SCMs) [8, 19].

To ensure analytical rigor, the following hypotheses are tested: H1: Partial replacement of OPC with (SCMs ≥ 30%) reduces embodied carbon compared to conventional mixes within the same strength class [8, 19]. H2: Cement-related emissions account for more than 80% of the total embodied carbon per cubic meter of concrete, [6, 8, 9]. H3: Higher concrete strength classes exhibit higher embodied carbon intensity due to increased cement content [7, 8]. H4: Typology-based scaling produces programme-level estimates within an acceptable deviation from aggregated building-level results [16, 25]. H5: Variations in cement emission factors have a greater influence on total emissions than variations in electricity or aggregate [8, 27].

The study is guided by the following research questions: (i) What is the embodied carbon intensity of structural concrete in post-earthquake reconstruction? (ii) How does partial substitution of OPC with SCMs affect embodied carbon under realistic conditions? (iii) Which parameters most strongly influence the results? (iii) How do the results compare with state-of-the-art benchmarks from EPD datasets and international LCA studies [14, 21, 22]?

Scientific Novelty Beyond Contextual Application

Life cycle assessment of concrete and the use of Monte Carlo simulation are well established in the literature [13, 37–40]. For this reason, the novelty of this study does not lie in the use of these methods individually. It is also not limited to the fact that the analysis is carried out in Albania. Previous studies have already applied LCA to concrete materials or individual buildings under standard conditions [8, 14, 22].

The contribution of this study lies in how these elements are combined. First, the analysis is based on real structural data derived from construction documentation. This improves the accuracy of material quantities compared to studies that rely only on generic datasets [13, 15]. Second, the study integrates probabilistic modelling into the assessment.

Uncertainty is explicitly quantified using Monte Carlo simulation, which allows the results to be expressed as ranges rather than single values [37–40]. A further contribution is the extension of the analysis from the building level to the programme scale. Most existing studies focus on materials or single buildings and do not address large-scale reconstruction processes [15, 16]. In this study, typology-based scaling is used to estimate emissions for a group of 100 buildings constructed under similar design conditions. This provides an order-of-magnitude assessment of emissions at the urban reconstruction level.

Taken together, the study links three elements that are rarely combined in the literature: real structural data, probabilistic life cycle assessment, and programme-scale estimation. This integrated approach allows a more consistent evaluation of embodied carbon in post-earthquake reconstruction and supports decision-making in large-scale construction programmes [16, 25]. This distinguishes the present study from existing LCA applications, which typically address either material-level or building-level analysis, but not their integration at programme scale.

METHODOLOGY

Goal and scope definition

This study applies a probabilistic process-based life cycle assessment (LCA) framework to quantify the embodied carbon associated with structural concrete used in post-earthquake residential reconstruction in Durres, Albania [13, 27]. The methodology follows the principles of ISO 14040 and ISO 14044 standards [30], with an extended formulation to explicitly account for parameter uncertainty and statistical variability, which are often neglected in deterministic LCA studies [13, 15]. The primary objective is to estimate greenhouse gas emissions associated with concrete production and to evaluate the influence of key material parameters under uncertainty. Unlike conventional approaches, the present study integrates stochastic modelling and uncertainty propagation, enabling the derivation of confidence intervals for embodied carbon results [13, 15].

Two functional units are defined. The primary functional unit is the embodied carbon per cubic meter of concrete (kg CO_2-eq/m^3), used to compare different concrete strength classes (C20/25, C25/30, C30/37). A secondary functional unit, expressed as kg CO_2-eq per square meter of gross floor area (kg CO_2-eq/m^2), is used to enable comparison at the building level and to support aggregation at programme scale [13]. The system boundary is defined as cradle-to-gate (A1–A3), including raw material extraction, cement production, aggregate processing, and concrete batching. While downstream stages (A4–A5, C1–C4) are excluded from the core model, their potential influence is evaluated through sensitivity considerations to ensure consistency with EN 15804 comparability principles [14, 27]. This approach is consistent with recommendations by Hoxha et al. (2020) [31] regarding the application of LCA in urban infrastructure assessments. The impact assessment focuses on global warming potential (GWP), expressed as CO_2-equivalents, based on IPCC characterization factors [31]. Emission factors are derived from validated literature sources and national datasets, ensuring consistency with established LCA practice [13, 27].

Case Study and Representativeness

The analysis is based on a post-earthquake reconstruction programme implemented in Durres, Albania, following the 2019 seismic event [1, 4]. The programme is characterized by the extensive use of reinforced concrete systems and standardized design solutions across residential buildings. Two newly constructed buildings were selected as representative case studies based on structural typology, concrete strength classes, and construction period. Both buildings consist of reinforced concrete frame systems with shear walls and were designed in accordance with Eurocode-based seismic provisions [32, 33]. The selection reflects the high level of standardization within the reconstruction programme. The two typologies represent 62% and 38% of the reconstructed building stock, respectively, according to the permit database. This distribution provides a consistent basis for extrapolating building-level results to programme scale.

The analysed buildings are representative of a broader sample of 100 residential buildings constructed under the same programme between 2019 and 2024 [1, 3, 5]. Their comparable structural configurations, material specifications, and construction practices support the generalization of material quantities and emission estimates with limited uncertainty [15]. By combining detailed building-level analysis with typology-based scaling, the methodology enables the estimation of embodied carbon at the reconstruction programme scale.

Figures 1 and 2 illustrate the urban-scale context of the case study, including the extent of earthquake-induced damage and the spatial distribution of reconstruction activities, supporting the selection of representative buildings

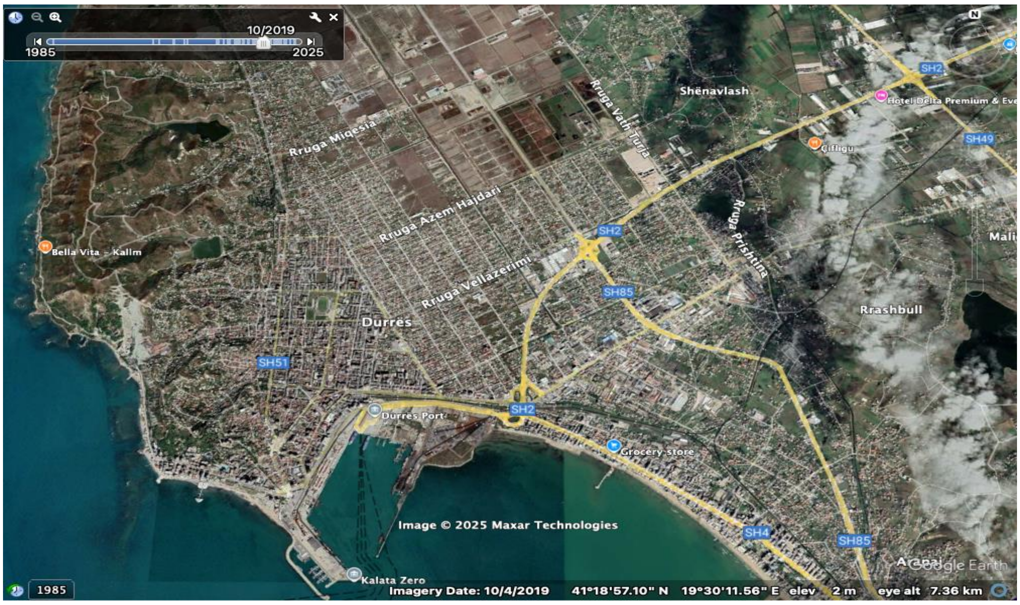


Figure 1 Urban layout of the city of Durres before the 2019 earthquake (Source: Google Earth, imagery date 2019; author´s annotation)

The spatial distribution of the reconstructed residential buildings and the selected case study buildings is shown in Figure 2.

Figure 2 Spatial distribution of the 100 multifunctional residential buildings constructed under the national post-earthquake reconstruction program in Durres, Albania (red), and location of the two representative buildings selected for detailed life-cycle assessment (blue)

Inventory data and material quantification

Material inventory data were obtained from construction permits, structural drawings, technical documentation, and on-site measurements. The analysis focuses on ready-mixed concrete used in load-bearing structural elements, including columns, beams, slabs, and shear walls. Concrete quantities were calculated from structural documentation and aggregated by strength class (C20/25, C25/30, C30/37), in accordance with EN 206-1 and Eurocode 2 standards [32, 33]. The use of project-specific data improves the reliability of the life cycle inventory (LCI) and reduces uncertainty in material estimation [13]. All material quantities are expressed per functional unit and linked to the emission model described in Section "Emission Model".

Table 4 summarizes the geometric and structural characteristics of the two representative buildings.

Table 5 reports the total volume of ready-mixed concrete. The combined concrete volume of 13,203.5 m^3 provides a representative basis for assessing material use within the reconstruction programme.

Table 4 Geometric and functional characteristics of two representative post-earthquake buildings.

	Building 1	**Building 2**
	Residential/service	Residential/service
Land area:	7,730.0 m^2	485.0 m^2
The plot area occupied by the structure	2,289.0 m^2	412.0 m^2
Building surface on land	19,538.0 m^2	2,810. m^2
Construction area underground	4,155.0 m^2	486.0 m^2
Total construction area	23,694.0 m^2	3,296.0 m^2
Overall height:	29.58 m	24.1 m
Number of floors above ground	9 floors and 3 floors	7 floors
Number of underground floors	1 floor	1 floor
Year of construction	From 2022 to 2024	From 2022 to 2024

Note: *Building 1 is composed of two volumes: one with 9 floors (main volume) and 3 floors (secondary volume).*

Table 5 Total volume of ready-mixed concrete used in the two representative post-earthquake buildings.

Building	**Concrete volume (m^3)**
Building 1	11,341.5
Building 2	1,862.0
Total	13,203.5

The two buildings use concrete strength classes C20/25, C25/30, and C30/ defined according to EN 206-1 (2000) and Eurocode 2 (EN 1992-1-1, 2004) [32, 33]. Differences between these classes are primarily related to mix composition, including cement, coarse aggregates, fine aggregates, and water (C: CA: FA: W), which are quantified in this study. Table 6 presents the distribution of concrete strength classes across the two buildings. The predominance of C25/30 concrete reflects its role as the standard strength class in mid-rise reinforced concrete buildings designed under seismic provisions [32, 33]. Variations in concrete strength class directly influence cement content, determining embodied carbon per cubic meter of concrete. Material quantities derived from design documentation were verified through consistency checks and comparison with construction practices to ensure data reliability. Remaining variability in input parameters is addressed through sensitivity analysis. The selected buildings share identical reinforced concrete structural systems, standardized concrete mix specifications, and construction periods with the majority of the reconstructed building stock [1, 3, 5].

Table 6 Distribution of concrete strength classes and corresponding volumes in the two representative post-earthquake buildings.

Concrete class	**Building 1(m^3)**	**Building 2(m^3)**	**Total (m^3)**
C20/25	641.0	76.0	717.0
C25/30	8,322.0	1,786.0	10,108.0
C30/37	2,378.5	-	2,378.5
Total			13,203.5

The load-bearing configurations, including columns, beams, slabs, and shear walls, are consistent across typologies. This consistency supports the use of typology-based scaling and enables the extrapolation of material quantities and associated emissions to the broader reconstruction programme with limited uncertainty [7].

Emission Model

CO_2 emissions from ready-mixed concrete production were quantified based on the main contributions: cement, coarse aggregates, fine aggregates, and electricity used in the mixing process. The analysis follows the defined system boundary (A1–A3), excluding on-site construction activities and downstream processes. The total emission factor per unit volume of concrete is calculated as [27, 34]:

$$EF = W_c \times EF_c + W_{ca} \times EF_{ca} + W_{fa} \times EF_{fa} + EF_m \quad (1)$$

Where:

EF is the total emission factor (kg CO_2 -eq/m^3); W_c, W_{ca}, and W_{fa} represent the material quantities of cement, coarse aggregates, and fine aggregates per cubic meter of concrete (kg/m^3), respectively, and EF_c, EF_{ca}, and EF_{fa} are the corresponding emission factor (kg CO_2 -eq/kg). EF_m represents emissions associated with the mixing process (kg CO_2 -eq/m^3).

All emission factors are expressed in consistent units. Total emissions from concrete production are calculated as [35, 36]:

$$E_{total} = V \times EF \quad (2)$$

Where:

V represents the total volume of concrete (m^3). Emissions associated specifically with the mixing process are calculated as [35, 36]:

$$E_{mix} = V \times EF_m \quad (3)$$

This modelling assumes a linear relationship between material quantities and associated emissions, consistent with established LCA practices for construction materials [27, 35]. Emission factors were obtained from standardized databases and validated publications [13, 28]. While the above formulation provides a deterministic estimate of embodied carbon, it does not account for variability in material properties and emission factors. To address this limitation, a probabilistic extension of the emission model is introduced [37-41]. The embodied carbon of concrete per unit volume is initially defined as:

$$EF = \sum_{i=1}^{n} m_i * EF_i \quad (4)$$

Where:

EF represent the emission factor of concrete (kg CO2)-eq/m^3); m_i is the mass of component i (kg/m3), and EF_i are the emission factor of the component i (kg CO2)-eq/m^3). To account for variability, material quantities and emission factors are treated as random variables:

$$m_i \sim N\,(\mu_i, \sigma_{m_i}) \tag{5}$$

$$EF_i \sim N(\mu EF_i, \sigma_{EF_i}) \tag{6}$$

The emission factor is then expressed as:

$$EF = \sum_{i=1}^{n} m_i * EF_i + \varepsilon \tag{7}$$

Where ε represents residual uncertainty due to model simplifications. Assuming independence between variables, the variance of EF is given by:

$$\sigma_{EF}^2 = \sum_{i=1}^{n}\left[(m_i \cdot \sigma_{EF_i})^2 + (EF_i \cdot \sigma_{m_i})^2\right] \tag{8}$$

Standard deviations are indicated as $\sigma_{m_i}$and σ_{EF_i} for material quantities and emissions factors, respectively:

$$\sigma_{EF} = \sqrt{\sigma_{EF}^2} \tag{9}$$

Uncertainty is propagated using a Monte Carlo simulation [37, 40, 41]. For each simulation k:

$$EF^{(k)} = \sum_{i=1}^{n} m_i^{(k)} \cdot EF_i^{(k)} \tag{10}$$

$$E^{(k)} = V^{(k)} \cdot EF^{(k)} \tag{11}$$

Where V represents the concrete volume, $k=1, 2, 3, \dots N$, within a total of $N=10{,}000$ simulations are performed to ensure statistical convergence [37-42]. The results are expressed as:

$$\bar{E} = \frac{1}{N}\sum_{k=1}^{N} E^{(k)} \tag{12}$$

$$\sigma_E = \sqrt{\frac{1}{N-1}\sum_{k=1}^{N}(E^{(k)} - \bar{E})} \tag{13}$$

$$CI = \bar{E} \pm 1.96 \cdot \sigma_E \tag{14}$$

$$E_{median},\ CI_{2{,}5\%-9{,}7\%} \tag{15}$$

The probabilistic model is used to quantify uncertainty and derive confidence intervals, while deterministic sensitivity analysis is applied to assess the influence of individual parameters [37, 38].

Electricity Consumption and Emission Factors

Electricity consumption associated with concrete mixing is included within the A1–A3 system boundary and incorporated into the emission model through the parameter EF_m [28]. An average electricity demand of 2.15 kWh/m^3 is adopted based on literature values for batching plant operations [28]. The emission factor reflects the characteristics of the Albanian energy system, which is predominantly based on hydropower but subject to variability due to electricity imports. A baseline value of 0.025 kg CO_2-eq/kWh is used to represent hydropower-dominated conditions, while higher values in the range of 0.05–0.10 kg CO_2-eq/kWh are considered to capture periods of increased imports [43, 44]. This range is incorporated into the sensitivity analysis to evaluate the influence of electricity-related parameters on total embodied carbon. Although the contribution of electricity is minor compared to cement production, its inclusion ensures completeness of the emission model and supports a consistent assessment of parameter sensitivity [8, 9].

Sensitivity Analysis

To evaluate the influence of key parameters on embodied carbon, a sensitivity analysis is performed. The analysis considers variability in cement emission factors (±10–15%), material quantities (±5%), and electricity emission factors (±10%), based on reported ranges in the literature [13, 27, 28]. A one-at-a-time (OAT) approach is applied, where each parameter is varied independently while others remain constant. The sensitivity analysis is conducted to identify the dominant parameters influencing embodied carbon [43]. The sensitivity coefficient for each parameter x_i is defined as:

$$S_i = \frac{\partial E}{\partial x_i} \cdot \frac{x_i}{E} \tag{16}$$

A global sensitivity indicator based on the variance contribution is defined as [38-43]:

$$S_i^{global} = \frac{\sigma_i^2}{\sigma_{total}^2} \tag{17}$$

Statistical testing is used to evaluate differences between scenarios (e.g., OPC vs SCM substitution). Independent *t-tests* are applied for normally distributed samples, while Wilcoxon rank-sum tests are used for non-parametric validation [38]. The test statistic is:

$$t = \frac{\overline{x_1 - x_2}}{S_p \sqrt{\frac{1}{n_i} + \frac{1}{n_2}}} \tag{18}$$

Where S_p is the pooled standard deviation:

$$S_p = \sqrt{\frac{(n_1 - 1)\sigma_1^2 + (n_2 - 1)\sigma_2^2}{n_1 + n_2 - 2}} \tag{19}$$

To quantify the influence of cement content on emissions, a linear regression model is applied [43].

$$EF = \alpha + \beta \cdot m_{cement} \tag{20}$$

The coefficient of determination (R^2) is used to assess model performance. The effect of concrete strength class is evaluated using ANOVA [27, 43].

$$EF = f(strength\ class) \tag{21}$$

Programme -scale emissions are estimated as:

$$E_{program} = \sum_{j=1}^{n} V_j \cdot EF_j \quad (22)$$

with associated uncertainty [37, 38]:

$$\sigma_{program} = \sqrt{\sum_{j=i}^{N} \sigma_j^2} \quad (23)$$

assuming independence between building-level emissions.

Results are expressed as percentage deviations from baseline values to enable comparison across concrete strength classes. Given the use of project-specific data and a limited number of representative case studies, a deterministic sensitivity approach is adopted. This provides a transparent assessment of parameter influence, while probabilistic analysis is used to quantify uncertainty and derive confidence intervals [37, 38].

Table 7 System boundaries and data sources for the cradle-to-gate life cycle assessment of ready-mixed concrete

Life cycle stage	Included activity	Included in analysis	Data source
Raw material production	Extraction and processing of aggregates and clinker	Yes	Scientific literature and a standardized database [6]
Cement production	Clinker calcination and grinding (OPC)	Yes	National GHG Inventory Report [24]
Concrete batching	Production of ready-mixed concrete	Yes	Scientific literature [13]
Electricity for concrete mixing	Electricity consumption (kWh/m^3)	Yes	Scientific literature [28]

RESULTS

This section presents cradle-to-gate CO_2 emissions from ready-mixed concrete in the two representative buildings. Both deterministic and probabilistic results are reported. Uncertainty in material quantities and emission factors is addressed using Monte Carlo simulation (N = 10,000), with results expressed as median values and 95% confidence intervals [37-41]. Tables 8–13 summarizes material quantities and corresponding embodied CO_2 emissions per cubic meter of concrete, as well as total emissions at the building level for the three strength classes (C20/25, C25/30, and C30/37). Emission intensity increases with concrete strength [8, 43]. The probabilistic results indicate emission intensities of 272 [255–290] kg CO_2-eq/m^3 for C20/25; 323 [300–345] kg CO_2-eq/m^3 for C25/30, and 349 [325–375] kg CO_2-eq/m^3 for C30/37. The increase between C20/25 and C30/37 is approximately 28.3% [7, 8].

Table 8 Material quantities and embodied CO_2 emissions for C30/37 concrete (per m^3)

Component	Quantity (kg m^{-3})	Emission factor (kg CO_2-eq kg^{-1})	Emissions (kg CO_2-eq m^{-3})
Cement	350.000	0.850	297.500
Coarse aggregates	1,040.000	0.046	47.840
Fine aggregates	877.000	0.0039	3.420
Total	-	-	348.760

Note: *Emissions are calculated per cubic meter of concrete. CO_2-eq denotes carbon dioxide equivalents.*

Table 9 Total CO_2 emissions associated with C30/37 concrete used in the analyzed buildings.

Parameter	Unit	Value
Concrete volume (C30/37)	m^3	2,378.5
Emission intensity	t CO_2-eq m^{-3}	0.349
Total emissions from concrete production	t CO_2-eq	829.1
Emissions from concrete mixing at plant	t CO_2-eq	2.9

Table 10 Material quantities and embodied CO_2 emissions for C25/30 concrete (per m^3)

Component	Quantity (kg m^{-3})	Emission factor (kg CO_2-eq kg^{-1})	Emissions (kg CO_2-eq m^{-3})
Cement	320.0	0.850	272.000
Coarse aggregates	1,030.0	0.046	47.380
Fine aggregates	860.0	0.0039	3.354
Total	–	–	322.734

Note: *Emissions are calculated per cubic meter of concrete. CO_2-eq denotes carbon dioxide equivalents.*

Table 11 Total CO_2 emissions associated with C25/30 concrete used in the analyzed buildings.

Parameter	Unit	Value
Concrete volume (C25/30)	m^3	10,108.0
Emission intensity	t CO_2-eq m^{-3}	0.323
Total emissions from concrete production	t CO_2-eq	3,264.9
Emissions from concrete mixing at plant	t CO_2-eq	12.40

Table 12 Material quantities and embodied CO_2 emissions for C20/25 concrete (per m^3)

Component	Quantity (kg m^{-3})	Emission factor (kg CO_2-eq kg^{-1})	Emissions (kg CO_2-eq m^{-3})
Cement	260.0	0.850	221.000
Coarse aggregates	1,030.0	0.046	47.380
Fine aggregates	940.0	0.0039	3.670
Total	–	–	272.050

Note: *Emissions are calculated per cubic meter of concrete. CO_2-eq denotes carbon dioxide equivalents.*

Table 13 Total CO_2 emissions associated with C20/25 concrete used in the analyzed buildings.

Parameter	Unit	Value
Concrete volume (C20/25)	m^3	717.0
Emission intensity	t CO_2-eq m^{-3}	0.272
Total emissions from concrete production	t CO_2-eq	195.02
Emissions from concrete mixing at plant	t CO_2-eq	0.890

The volume-weighted average CO_2 intensity and the total cradle-to-gate emissions for the two buildings are presented in Table 14. These results correspond to emissions associated with raw material production and concrete batching, in line with the defined system boundaries (A1–A3) [14]. The weighted average emission intensity of 0.325 t CO_2-eq/m^3 reflects the distribution of concrete strength classes and their respective volumes [13]. C25/30 concrete accounts for the largest share of total concrete volume and dominates total emissions at the building level [8, 13].

Table 14 Total cradle-to-gate CO_2 emissions associated with structural concrete in the two representative buildings

Parameter	Unit	Value
Total volume of concrete	m^3	13,203.5
Total CO_2 emissions (material production)	t CO_2-eq	4,289.02
Total CO_2 emissions (concrete mixing at plant)	t CO_2-eq	16.19
Weighted average CO_2 intensity	t CO_2-eq m^{-3}	0.325

Note: *The weighted average CO_2 intensity is calculated as $\sum(V_i * EF_i) / \sum V_i$ where V_i and EF_i represent the volume and emission intensity of each concrete strength class.*

Under the probabilistic framework, the weighted average emission intensity is estimated at 0.325 [0.298–0.356] t CO_2-eq/m^3. The relatively narrow confidence interval (~ ±9%) indicates limited variability in the input parameters and suggests a high level of result stability [37-41].

The contribution of different concrete classes to total embodied carbon emissions is shown in Figure 3. The relative contribution of each class remains stable under uncertainty, while variations mainly affect absolute emission [37-41]. When normalized, the contributions are approximately 5% for C20/25, 76% for C25/30, and 19% for C30/37. To evaluate programme scale implications, results from the two representative buildings were extrapolated to 100 residential buildings reconstructed in Durres. Of these, 62 buildings correspond to the typology of Building 1, and 38 to Building 2 [1, 3, 5, 29]. This distribution was used to scale emissions based on observed typologies [15]. Total cradle-to-gate emissions from structural concrete are estimated at approximately 215,261 t CO_2-eq, including both material production and concrete mixing within A1–A3 system boundaries [14]. When uncertainty is propagated through the scaling model, total programme emissions range between approximately [196,000–238,000] t CO_2-eq, indicating variability at programme scale [37-41]. At the material level, C25/30 concrete contributes the largest share of total emissions due to its extensive use despite its lower emission intensity compared to higher-strength classes. In contrast, higher-strength concretes exhibit greater emission intensity, reflecting a higher cement content, which is consistent with previous findings [7, 8]. This result supports Hypothesis H3.

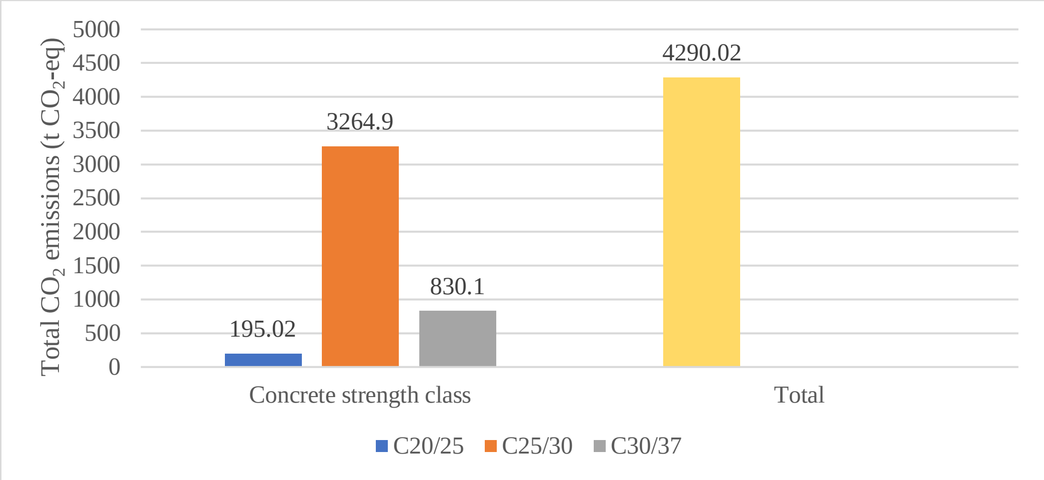


Figure 3 Absolute cradle-to-gate CO_2 emissions associated with structural concrete by concrete strength class in the two representative post-earthquake residential buildings. The total value represents the sum of emissions from all concrete strength classes.

Cement is identified as the dominant contributor to embodied carbon, supporting Hypothesis H2 [8, 9]. Sensitivity analysis shows that cement-related parameters have the strongest impact on total emissions, with coefficients in the range of 0.80–0.85 [27, 43]. In contrast, aggregates and electricity-related parameters show limited influence, with sensitivity values below 0.15 and 0.01, respectively [27]. The results os sensitivity analysis are presented in Figure 4.

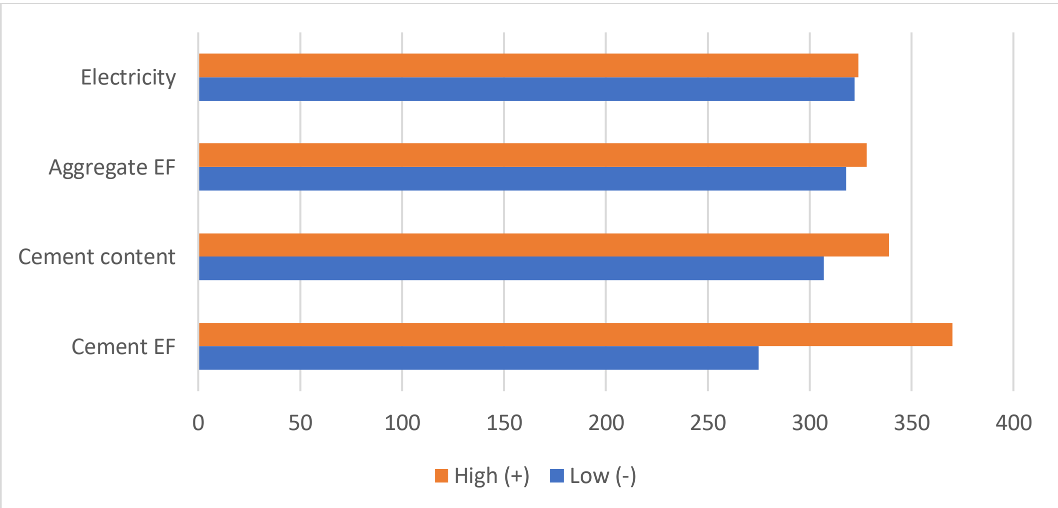


Figure 4 The sensitivity of embodied carbon (kg CO_2-eq/m³) to variations in key input parameters, including cement emission factor, cement content, aggregate emission factor, and electricity emission factor.

Cement-related parameters also dominate the variability of embodied carbon, supporting Hypothesis H5 [27, 43]. Statistical analysis confirms this relationship. Linear regression between cement content and emission intensity yielded a coefficient of determination of $R^2 \approx 0.87$. Differences between concrete strength classes are statistically significant ($p < 0.01$), supporting the hypothesis H3 [27, 43].

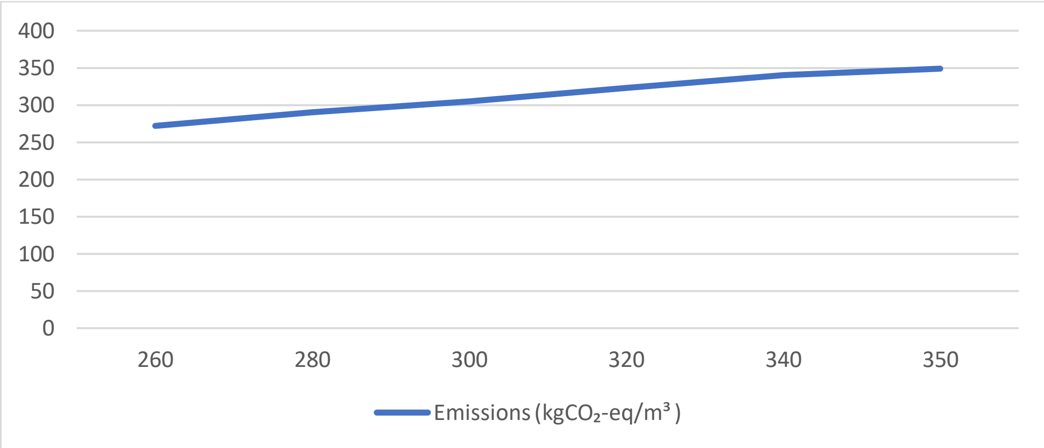


Figure 5 Relationship between cement content (kg/m³) and embodied carbon (kg CO_2-eq/m³) for the analysed concrete strength classes, including linear regression fit.

DISCUSSION

The results show that embodied carbon in post-earthquake reconstruction is mainly driven by material production, with cement as the dominant emissions source, consistent with previous studies [8, 9]. This is due to the much higher emission factor of cement compared to other concrete components. In contrast, emissions related to concrete mixing are very low, accounting for less than 1% of total embodied carbon. This is linked to the low electricity emission factor and the limited energy demand of batching processes. As a result, variations in electricity-related parameters have only a minor effect on total emissions within A1–A3 system boundaries [8, 9]. The calculated emission intensity of 0.325 t CO_2-eq/m³ falls within the range reported in the literature for post-earthquake reconstruction. Similar values have been observed in Nepal (0.270–0.340 t CO_2-eq/m³) [25], Turkey (approximately 0.320 t CO_2-eq/m³) [46], while higher values are reported in Haiti (>0.360 t CO_2-eq/m³), where conventional OPC-based mixes dominate [47]. Lower values, around 0.250 t CO_2-eq/m³, have been reported in the L'Aquila reconstruction in Italy, where the adoption of supplementary cementitious materials (SCMs) and optimized mix design contributed to emission reductions [47]. This indicates that current reconstruction practices are aligned with conventional concrete production, but remain distant from optimized low-carbon systems reported in the literature. Figure 6 places the results of this study within an international context.

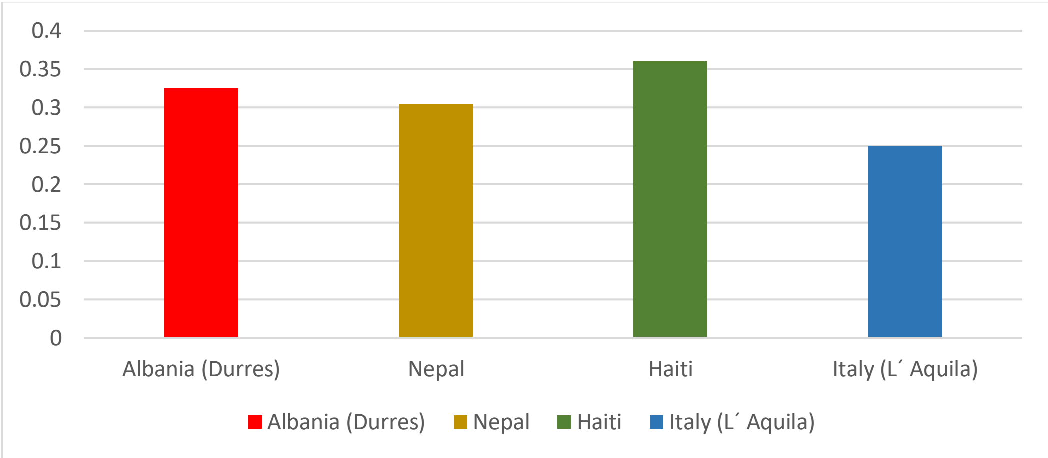


Figure 6 Comparison of embodied carbon intensity (t CO_2-eq/m^3) for structural concrete in post-earthquake reconstruction across selected case studies.

A normalized comparison places the results for Durres within the upper-middle range of reported emission intensities. Compared to low-carbon reconstruction scenarios, such as those observed in Italy, the results are approximately 30% higher. This difference reflects the absence of clinker reduction strategies and confirms the continued reliance on conventional OPC-based concrete mixes. This gap is not marginal, but structurally significant, as it reflects a systematic difference in material design rather than isolated project conditions. The relative contribution of material production and concrete mixing to total cradle-to-gate emissions is presented in Table 15. Material production clearly dominates total emissions, while the contribution of mixing remains negligible. This confirms that emission reduction efforts should focus on material composition rather than process-related factors.

Table 15 Contribution of material production and concrete mixing to total CO_2 emissions.

Categories	**Total Emission (t-CO_2-eq)**
Material	4,289.02
Mixing process at plant	16.19

The relationship between cement content and total emissions is direct: higher binder demand leads to higher embodied carbon. This highlights the potential for emission reduction through clinker substitution and optimized mix design. Figures 7 and 8 illustrate the results of the scenario analysis.

At the programme scale, extrapolation from the two representative buildings, based on their observed distribution (62% and 38%), yields an estimated total of approximately 215,261 t CO_2-eq for structural concrete across 100 reconstructed residential buildings. This result shows that programme-scale emissions are not simply an extension of building-level results, but represent a cumulative effect where repeated construction practices amplify total impact.

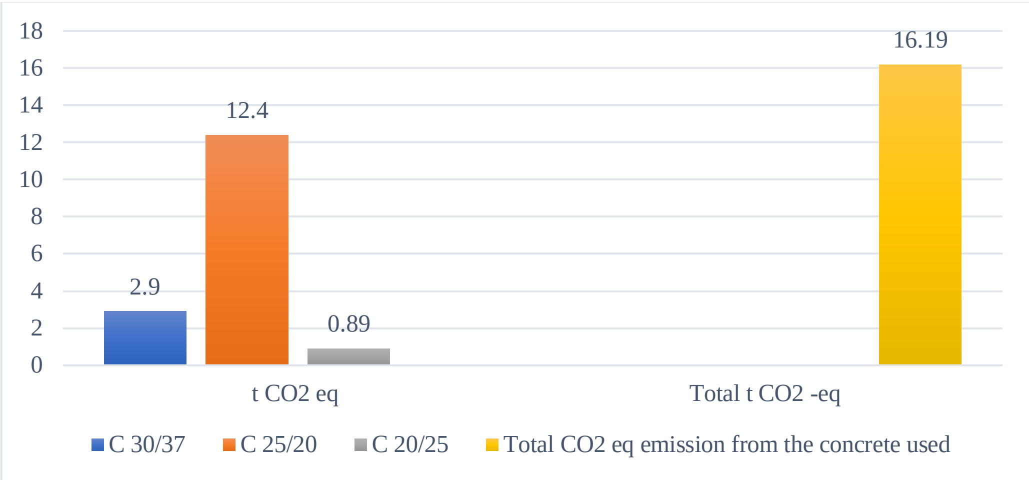
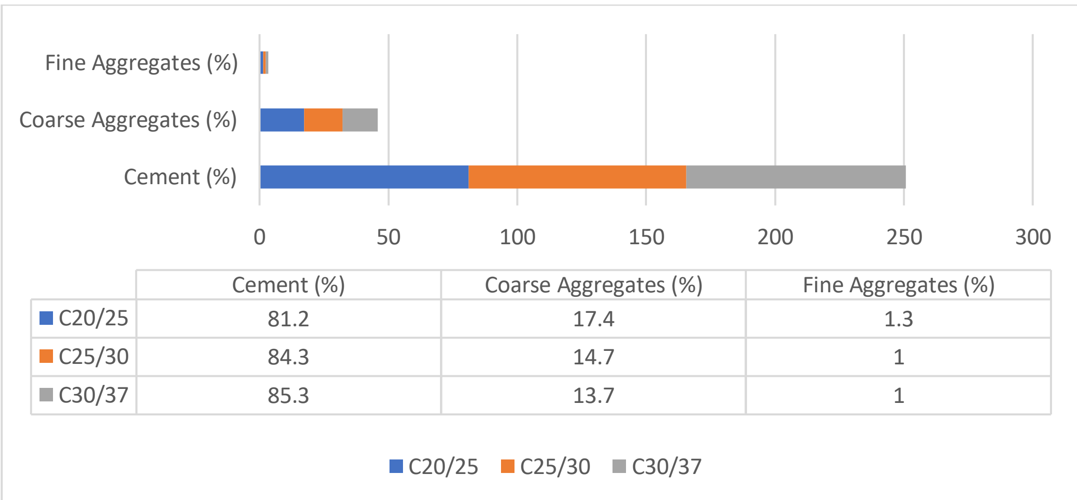


Figure 7. CO_2 emissions associated with concrete mixing at the ready-mix plant for each concrete strength class and total emissions for the two representative buildings.

This estimate assumes consistent structural typologies, material quantities, and construction practices. Within a probabilistic framework, it should be interpreted as an order-of-magnitude estimate, with an uncertainty of approximately ±10%, reflecting the combined variability of material quantities and emission factors.

The analysis of material contributions shows that cement accounts for approximately 81–85% of total emissions, while aggregates contribute less than 20% [6, 16]. This confirms that embodied carbon is highly concentrated as a single component. This concentration implies that emission reduction strategies can be highly effective if they target cement content, as changes in a single parameter can influence the majority of total emissions. The consistency of this pattern across all concrete classes indicates that embodied carbon is primarily governed by binder composition rather than aggregate proportions. This explains why variations in cement content have a much stronger impact than other parameters.



	Cement (%)	Coarse Aggregates (%)	Fine Aggregates (%)
C20/25	81.2	17.4	1.3
C25/30	84.3	14.7	1
C30/37	85.3	13.7	1

Figure 8. Percentage contribution of cement, coarse aggregates, and fine aggregates to total embodied CO_2 emissions for different concrete strength classes.

The results also show that mid-strength concrete (C25/30) contributes the largest share of total emissions due to its extensive use, even though its emission intensity is lower than that of higher-strength classes. This highlights that total emissions are driven not only by intensity, but also by volume distribution, making widely used concrete classes the most relevant targets for emission reduction. Targeting cement content through clinker substitution and optimized binder design can therefore lead to substantial reductions in embodied carbon. At the policy level, the scale of emissions associated with reconstruction in a single urban area highlights the need to align construction practices with climate targets, including commitments under the Paris Agreement and the EU accession framework [48]. The integration of LCA into early design and procurement processes can support more effective material selection and facilitate the adoption of low-carbon practices [49]. Although transport and construction phases were not included in this analysis, previous studies suggest that they may contribute an additional 10–15% to total emissions [47]. Their inclusion would improve completeness but is unlikely to alter the dominance of cement-related emissions. A comparative overview of carbon intensity values is provided in Table 16, positioning the results from Durres within an international context.

Table 16 Comparative CO_2 emissions from structural concrete in post-earthquake reconstruction

Country	**Carbon Intensity** (t CO_2-eq m^{-3})	**SCM used**	**Source**
Albania (Durres)	0.325	No	This study
Nepal	0.27–0.34	Yes	[25]
Haiti	>0.36	No	[47]
Italy (L'Aquila)	0.25	Yes	[47]

Note: *Reported values refer to cradle-to-gate system boundaries and structural concrete only.*

Scenario-Based Analysis of CO_2 Reduction through Cementitious Materials (SCMs)

A scenario-based analysis was performed to evaluate strategies for reducing embodied carbon in post-earthquake reconstruction. The analysis considers partial substitution of Ordinary Portland Cement (OPC) with Supplementary Cementitious Materials (SCMs). Previous studies [8, 27] show that SCM substitution can significantly reduce emissions from cement production while maintaining structural performance. Two scenarios were evaluated and compared with the baseline case. Scenario A assumes a 15% replacement of OPC, while Scenario B considers a 30% substitution. Emissions from aggregates and concrete mixing are assumed to remain unchanged, with reductions driven mainly by decreased cement content. The reduction in embodied carbon is expressed as [19]:

$$\Delta E = E_{baseline} - E_{SCM} \quad (24)$$

Where $E_{baseline}$ represents emission from conventional OPC-based concrete, and E_{SCM} corresponds to emissions after SCM substitution. Total emissions for each scenario are calculated as [19]:

$$E_{SCM} = \sum (V_i * EF_{i,SCM}) \quad (25)$$

Where V_i and $EF_{i,SCM}$ indicate the volume and emission intensity of each concrete strength class under SCM substitution, respectively.

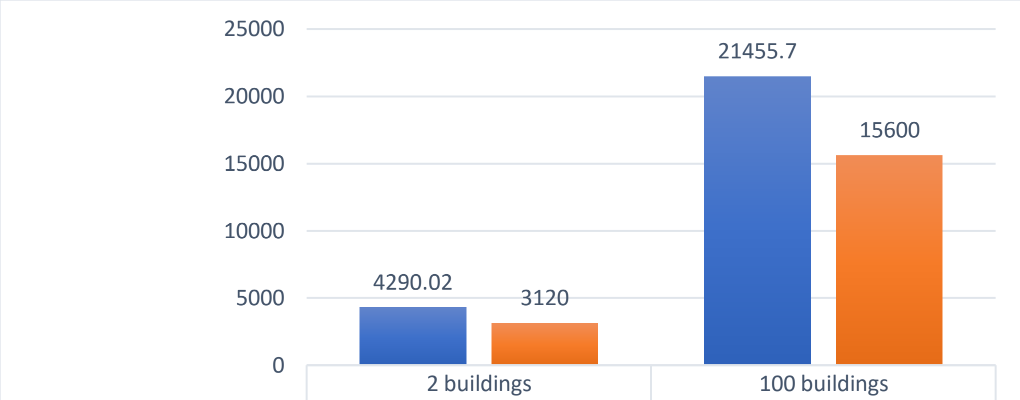
Table 17 summarizes the results. Under Scenario B (30% SCM substitution), total material-related emissions decrease from approximately 4,289 t CO_2-eq to 3,118 t CO_2-eq, corresponding to a reduction of about 27%. This reduction is substantial, as it is achieved through a single material-level intervention without changes in structural design or construction practices.

Table 17 Scenario-based reduction of cradle-to-gate CO_2 emission through partial substitution of ordinary Portland Cement with SCMs

Scenario	**OPC replacement** (%)	**Cement-related CO_2 emissions** (kg CO_2-eq m^{-3})	**Reduction vs. baseline** (%)	**Total CO_2 emissions for 13,203.5 m^3** (t CO_2-eq)
Baseline (actual practice)	0% (Pure OPC)	272–297 (depending on mix class)	-	4,289.02
Scenario A	15% SCM	230–240	13–15%	3,700–3,730
Scenario B	30% SCM	200–210	25–30%	3,120–3,130

Note: *Cement-related CO_2 emission ranges reflect variability across concrete strength classes. Total emissions are calculated assuming unchanged aggregate-related and mixing-related emissions, and are scaled based on the total concrete volume*

When extrapolated to 100 reconstructed residential buildings, this corresponds to a reduction of approximately 5.9×10^4 t CO_2-eq, decreasing total emissions from about 2.15×10^5 t CO_2-eq to 1.56×10^5 t CO_2-eq. At the programme scale, this demonstrates that relatively simple changes in material composition can lead to large cumulative emission reductions. These results confirm that SCM substitution is an effective strategy at both building and programme level. The reduction is mainly driven by the dominant contribution of cement identified in the baseline. This also indicates that emission reduction potential is concentrated in a limited number of design parameters, with cement content representing the most effective leverage point. The findings further show that emission reduction strategies should focus on widely used concrete classes such as C25/30, rather than only on high-strength mixes. Given their large share in total volume, these classes offer the greatest potential for impact.



	2 buildings	100 buildings
without SCM ($t\text{-}CO_2$)	4290.02	21455.7
With 30% SCM ($t\text{-}CO_2$)	3120	15600

Figure 9 Comparison of total cradle-to-gate CO_2 emissions from structural concrete with and without partial substitution of Ordinary Portland Cement (30% SCM) for the two representative buildings and for the extrapolated reconstruction stock of 100 buildings.

Environmental Policies and the Technical Feasibility of their Implementation

Scenario analysis indicates that partial substitution of OPC with SCMs can reduce embodied carbon by approximately 27%, corresponding to a reduction of about 5.9×10^4 t CO_2-eq at programme scale. Achieving such reductions in the Albanian context requires alignment between technical regulations, procurement practices, and implementation capacity. Current reconstruction practices rely primarily on conventional OPC-based concrete, and existing technical specifications do not explicitly support the use of SCMs. This limits their practical adoption despite established structural performance [8, 47]. Updating design guidelines would facilitate the integration of low-carbon materials. Public procurement plays a central role in large-scale reconstruction programmes. The inclusion of embodied carbon criteria could accelerate the adoption of low-carbon and influence production practices [50]. Implementation also depends on technical capacity and quality control. Strengthening collaboration between academia, industry, and public institutions would support the adoption of SCM-based solutions. Integrating life cycle assessment (LCA) into design and planning processes is essential for informed material selection and for reducing long-term carbon lock-in [49].

SUMMARY AND CONCLUSION

The post-earthquake reconstruction of Durres represents a material-intensive process with significant implications for embodied carbon at both building and programme scale. By integrating detailed structural inventory data within a life cycle assessment framework, this study provides the first empirical estimate of embodied carbon associated with post-disaster reconstruction in Albania.

The results indicate that structural concrete generates substantial emissions, with a volume-weighted intensity of 0.325 t CO_2-eq/m^3 and total programme emissions of approximately 2.15 × 10^5 t CO_2-eq. Cement is identified as the dominant contributor, accounting for 80–85% of total emissions, while emission intensity increases with concrete strength. At the same time, total emissions are driven by the combined effect of intensity and material distribution, with C25/30 concrete contributing the largest share due to its widespread use. Scenario analysis indicates that partial substitution of ordinary Portland cement with supplementary cementitious materials can reduce emissions by approximately 25–30%, resulting in substantial reductions at the program scale. This identifies mix design as a key intervention point for reducing embodied carbon. Overall, the findings demonstrate that conventional reconstruction practices based on reinforced concrete systems result in significant cumulative emissions. However, meaningful reductions are achievable within current engineering practice without compromising structural performance.

These results show that embodied carbon should be considered at the early design stage. It should not be treated only as a post-assessment indicator. The analysis indicates that material choices, especially cement content, have the strongest influence on total emissions. The use of life cycle assessment and low-clinker cement systems can therefore reduce emissions in post-earthquake reconstruction. This study also shows that combining structural data with probabilistic life cycle assessment makes it possible to estimate embodied carbon at programme scale in a consistent way. This addresses a limitation found in many existing studies.

AUTHOR'S CONTRIBUTIONS

Conceptualization, S.S.; methodology, S.S. and O.M.; software, S.S., and M.B.; validation, S.S., E.V. and O.M.; formal analysis, A.H. and J.S.; investigation, S.S., and O.M.; resources, S.S., and J.S.; data curation, S.S. and M.B.; writing—original draft preparation, S.S.; writing—review and editing, S.S. and O.M.; visualization, S.S. and J.S.; supervision, O.M.; project administration, S.S.

CONFLICT OF INTERESTS

The authors declare that there are no competing interests involved.

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