

Ground Granulated Blast Furnace Slag as a Sustainable Alternative to Cement in Low Carbon Concrete

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Abstract

Ground Granulated Blast Furnace Slag (GGBFS) is a byproduct of iron ore processing that can be reused. One of its applications is as a more environmentally friendly binder in concrete by partially replacing Ordinary Portland Cement (OPC). The production of OPC is one of the largest contributors to global carbon emissions, accounting for up to 8%. In this study, GGBFS is used as a cement substitute due to its high CaO content. The objective of this research is to determine the optimal substitution percentage of GGBFS for cement in terms of compressive strength, energy consumption, and carbon emissions. The substitution percentages used were 20%, 40%, 50%, 60%, and 80% by absolute volume of cement. Compressive strength was tested using cylindrical specimens with a diameter of 10 cm and a height of 20 cm. Tests were conducted on concrete at the ages of 7, 14, 28, and 56 days. Based on the results, the compressive strength at 56 days increased by 4.85% (34.49 MPa) at 20% substitution, but then decreased at 40%, 50%, 60%, and 80% by 11.84% (30.80 MPa), 6.87% (28.68 MPa), 0.74% (28.47 MPa), and 25.44% (21.23 MPa), respectively. Further analysis showed that carbon emissions decreased proportionally with the increasing percentage of GGBFS substitution. The reductions in carbon emissions for 20%, 40%, 50%, 60%, and 80% GGBFS substitution compared to normal concrete were 17.34%, 34.68%, 43.36%, 52.03%, and 69.37%, respectively. The most optimal substitution percentage, considering compressive strength, energy use, and carbon emissions, was found to be 40%, with an average 56-day compressive strength of 30.803 MPa, energy consumption of 1869.64 GJ/m³, and carbon emissions of 308.64 t-CO₂/m³.

Keywords: Ground Granulated Blast Furnace Slag (GGBFS), Less Cement Concrete, Low-Carbon Concrete

1. INTRODUCTION

Climate change caused by global warming is a critical environmental issue that negatively affects all living organisms on the planet. Global warming is primarily driven by the emission of greenhouse gases, including methane (CH₄), nitrous oxide (N₂O), and carbon dioxide (CO₂) into the atmosphere.[1]. Globally, it was reported that in 2022 the cement industry contributed approximately 8% of total CO₂ emissions. In the same year, Indonesia produced around 120 million tons of cement, and this figure is expected to continue increasing in line with the growing demand for concrete [2,3]. According to McCaffrey, it is estimated that the production of one ton of Portland cement releases approximately one ton of CO₂ into the atmosphere. As a result, the development of green concrete without the use of Ordinary Portland Cement (OPC) has become increasingly important and is now a prominent trend in the concrete industry. One such innovation is the use of Low Cement Concrete (LCC), which incorporates alternative binders and reduces the reliance on conventional cement.[4].

One of the practical applications of Low Cement Concrete (LCC) is the partial substitution of Ordinary Portland Cement (OPC) with Ground Granulated Blast Furnace Slag (GGBFS). GGBFS is a by-product of the iron manufacturing industry. During the iron-making process, iron ore is introduced into a blast furnace, where molten slag floats on top of the molten iron at temperatures ranging from 1500°C to 1600°C [5]. The molten slag typically consists of approximately 30–40% silicon dioxide (SiO₂) and about 40% calcium oxide (CaO), a chemical composition that is quite similar to that of Portland cement. The production of GGBFS requires significantly less energy, as it utilizes industrial waste material from the iron industry. Furthermore, concrete made with GGBFS as a binder emits substantially lower carbon emissions compared to conventional concrete made with OPC [6,7].

A previous study conducted by Rano Anwar et al. (2023) demonstrated that increasing the substitution level of cement with Ground Granulated Blast Furnace Slag (GGBFS) tends to result in a decrease in compressive strength. This trend was observed at substitution rates of 50% and 70% GGBFS, where the compressive strength at 28 days decreased by up to 10% compared to normal concrete. However, by day 60, the compressive strength became more stable, with a reduction ranging between 0% and 8% [8]. A similar trend was reported in a study by T. Vijayagowri (2014), which found that the compressive strength of GGBFS-based concrete was inversely proportional to the water-to-binder ratio. GGBFS concrete exhibited significantly higher strength at later ages (beyond 90 days). Vijayagowri noted that high-volume slag concrete gained higher strength over time due to the slow hydration rate of GGBFS when reacting with Ca(OH)₂ and water. The study concluded that replacing 50% of cement with GGBFS

not only reduces cement content and construction costs but also contributes to environmental protection by lowering pollution associated with cement production [9].

Ground Granulated Blast Furnace Slag (GGBFS) is considered one of the most environmentally friendly materials with significant potential to replace Ordinary Portland Cement (OPC) as the primary binder in concrete. The energy consumed in the production of OPC is approximately 4.53 GJ/m³, with associated carbon emissions of about 0.84 t-CO₂/m³. In contrast, GGBFS production requires significantly less energy—only 0.857 GJ/m³—and results in substantially lower emissions at 0.052 t-CO₂/m³ [10]. This study aims to build upon previous research by focusing on identifying the optimal GGBFS substitution ratio for OPC in concrete. The investigation emphasizes not only the mechanical performance (i.e., compressive strength) of the concrete but also the environmental impact, particularly in terms of carbon emissions.

1.1. Effects of Ground Granulated Blast Furnace Slag on Concrete

This section provides a brief overview of the effects of Ground Granulated Blast Furnace Slag (GGBFS) on the properties of concrete and the extent of its influence. It is important to note that the impact of GGBFS varies significantly depending on the replacement level used in the concrete mix.

Based on a review of various studies concerning the partial replacement of cement with GGBFS, several relevant conclusions can be drawn as follows: (1) All types of pozzolanic materials, including GGBFS, are effective in significantly reducing concrete permeability compared to control mixtures; (2) The workability of concrete improves with increasing levels of GGBFS replacement; (3) As the GGBFS content increases, the water-to-binder ratio tends to decrease for the same level of workability, indicating a positive effect of GGBFS on fresh concrete behavior; (4) In most cases, compressive strength decreases with higher GGBFS percentages at early ages, but improves at later ages due to continued hydration; (5) Similarly, splitting tensile strength and flexural strength tend to decline at early ages with increased GGBFS content, but show improvement at later curing stages; (6) Strength gain increases up to a certain replacement level, after which it begins to decline, though long-term strength continues to develop due to the slower reaction rate between GGBFS and calcium hydroxide (Ca(OH)₂); (7) The heat of hydration in GGBFS is significantly lower, which reduces the risk of thermal cracking and makes it suitable for high-temperature construction environments; (8) Concrete resistance to chloride and sulfate attack improves as GGBFS content increases; (9) GGBFS-based concrete exhibits minimal initial absorption, indicating that the surface of the mix is virtually impermeable; (10) Replacing cement with GGBFS helps reduce the overall cement content in concrete, leading to lower construction costs, as GGBFS is approximately 25–50% cheaper than Ordinary Portland Cement (OPC); (11) The reuse of slag contributes to environmental protection by reducing CO₂ emissions; (12) Concrete with partial GGBFS replacement demonstrates enhanced resistance to carbonation and sulfide attack; and (13) The incorporation of GGBFS slightly improves the elastic modulus of concrete for a given compressive strength when compared to OPC-based concrete.

1.1.1. Setting Time

An increase in setting time is commonly observed when Ground Granulated Blast Furnace Slag (GGBFS) is used as a partial replacement for Portland cement in concrete mixtures. The extent of this effect on setting time depends on several factors, including the initial temperature of the concrete, the mix proportions, the water-to-cementitious materials ratio, and the specific characteristics of the Portland cement used. In general, concrete containing GGBFS tends to exhibit longer setting times compared to similar concrete made solely with Ordinary Portland Cement (OPC). The setting time typically increases with higher GGBFS content. Peter W.C. Leung also reported that GGBFS concrete requires a longer setting time than OPC concrete, which may be attributed to the smooth, glassy, and fine nature of GGBFS particles. Moreover, the setting time becomes more prolonged as the percentage of GGBFS replacement increases. It is also noted that GGBFS concrete is particularly sensitive to low ambient temperatures, which can further delay the setting process [11].

Wainwright and Ait-Aider (1995) investigated the effects of GGBFS addition on the setting time and consistency of cement. In their study, cement samples from three different sources and GGBFS from a single source were used. The cement was partially replaced with 40% and 70% GGBFS. The study concluded that: (i) the consistency and setting time results were relatively similar across all cement sources; (ii) the incorporation of GGBFS influenced the consistency of the cement paste, which decreased with increasing GGBFS content; and (iii) the setting time increased as the GGBFS content increased [12].

More recently, Baždarić, Jurić, and Baričević (2023) also investigated the setting behavior of GGBFS when used as a binder in concrete. Their results confirmed that GGBFS exhibits a slower setting time compared to Ordinary Portland Cement (OPC). This behavior is attributed to the lower hydraulic reactivity of GGBFS. Unlike OPC, which reacts immediately with water, GGBFS initially reacts with calcium hydroxide [Ca(OH)₂] released during the hydration of cement. As a result, the initial formation of calcium silicate hydrate (C-S-H) gel is delayed in GGBFS systems, leading to a slower early-stage setting process compared to OPC [13].

1.1.2. Workability

Wood (1981) reported that the workability and placing ability of concrete containing Ground Granulated Blast Furnace Slag (GGBFS) exhibited improved characteristics compared to concrete without slag. He further explained

that this improvement was attributed to the surface characteristics of GGBFS, which create smooth slip planes within the cement paste [14]. Bahador Sabet Divsholi et al. also reported that slump and fluidity increased with higher percentages of GGBFS replacement. For a water-to-cementitious material ratio (w/cm) of 0.5 and an aggregate-to-cementitious material ratio (a/cm) of 3.0, slump increased by 20%, 35%, and 55% for 10%, 30%, and 50% GGBFS replacement levels, respectively [15]. The findings of Divsholi et al. are consistent with those of Neville (2011) in his book *Properties of Concrete*, where he stated that GGBFS contributes to improved workability compared to OPC. This is primarily due to the finer particle size of GGBFS and its lower initial water demand, owing to its slower hydration rate compared to OPC. Furthermore, GGBFS exhibits lower water absorption, measured at approximately 1.2%, compared to 1.5% for OPC, which contributes to its enhanced fresh concrete behavior [6].

1.1.3. Compressive Strength

Vinayak Awasare studied the strength characteristics of M20 grade concrete by replacing Ordinary Portland Cement (OPC) with Ground Granulated Blast Furnace Slag (GGBFS) at levels of 30%, 40%, and 50%, and compared the results to conventional concrete. In this study, manufactured sand was also used to replace natural sand, broadening the research scope to determine the optimum replacement percentage using both crushed and natural sand. The control concrete was prepared with OPC and crushed sand of M20 grade. The maximum compressive strength achieved was 29.78 MPa at 30% GGBFS replacement, while the strengths achieved for 20%, 40%, and 50% replacements were 27.11 MPa, 26.37 MPa, and 22.22 MPa, respectively. These values were compared with the 25.61 MPa compressive strength of the conventional OPC concrete after 28 days [16].

Santosh Kumar Karri et al. also adopted 30%, 40%, and 50% as cement replacement levels and tested M20 and M40 grade concrete specimens after curing for 28 and 90 days. The results revealed that even with 50% OPC replacement, the target compressive strength was still achieved by day 90 for both M20 and M40 grades. The study further observed that the maximum compressive strength, split tensile strength, and flexural strength occurred at 40% GGBFS replacement in both concrete grades. Although a slight decrease in strength was noted, the values remained within acceptable limits [17].

According to Maitri Mapa et al., the negative impact of GGBFS incorporation on compressive strength diminishes with increased curing age. This is likely due to the initially slow pozzolanic reaction of GGBFS, which is primarily dependent on the availability of calcium hydroxide and silica. As curing age increases, the rate of reaction tends to accelerate, thereby delaying strength development in GGBFS-blended mortar. However, the compressive strength reduction was not clearly evident in CEM20GS specimens across all curing ages or in CEM40GS specimens at 28 and 90 days. In contrast, a clear negative impact on mechanical strength was observed for higher replacement levels of 60% and 80% GGBFS, across all curing durations. Compared to the control cement mortar cubes, the compressive strength of CEM20GS declined by 9.58% (Day 1), 15.87% (Day 3), 20.75% (Day 7), 9.11% (Day 28), and 4.08% (Day 90). For CEM40GS mortar cubes, the reductions were 14.25% (Day 1), 31.16% (Day 3), 30.45% (Day 7), 12.75% (Day 28), and 6.62% (Day 90). The CEM60GS mortar exhibited even more significant losses, with strength reductions of 61.70%, 64.96%, 64.03%, 43.59%, and 28.11% on days 1, 3, 7, 28, and 90, respectively, compared to the control [18].

1.1.4. Environmental Assessment

Carbon dioxide (CO₂) emissions are primarily caused by the oxidation of carbonates during the production of cement clinker, which is the main component of cement and represents the most significant non-combustion-related source of CO₂ emissions from industrial processes. This process accounted for approximately 4.8% of total global CO₂ emissions in 2013. Additionally, CO₂ emissions from fuel combustion during cement production are approximately equal in magnitude, bringing the total contribution of cement manufacturing to around 9.5% of global CO₂ emissions. The use of slag cement offers numerous environmental benefits, including energy savings, reductions in greenhouse gas emissions, and decreased consumption of virgin raw materials [26]. It is also implied that the use of Ground Granulated Blast Furnace Slag (GGBFS) can significantly reduce CO₂ emissions per ton of cementitious material while utilizing a by-product of another industrial process [19].

The global average emission factor for producing one ton of cement—including transportation to a ready-mix concrete facility—is estimated at 0.91 t CO₂-e/ton. In contrast, this figure drops to just 0.143 t CO₂-e/ton for GGBFS. Cement manufacturing requires high temperatures to calcine raw materials and impart the desired properties to the clinker, a process that releases significant amounts of CO₂. The emissions primarily arise from three sources: (1) the decarbonation of limestone in the kiln, which produces approximately 525 kg of CO₂ per ton of clinker; (2) the combustion of fuel in the kiln, responsible for around 335 kg of CO₂ per ton of cement; and (3) electricity usage, which contributes about 50 kg of CO₂ per ton of cement [20].

GGBFS, produced as a by-product of iron manufacturing, exemplifies industrial ecology in its utilization. It can be used as a coarse aggregate or as a mineral admixture in concrete, replacing up to 80% of cement content and reducing CO₂ emissions by 60% to 70% per ton of concrete. GGBFS is commonly used to replace 35–65% of Portland cement in concrete. A 50% replacement of Portland cement with GGBFS can prevent approximately 0.5 tons of CO₂ from being released into the atmosphere. [21] A study was conducted to estimate the CO₂ emissions

associated with the production and placement of concrete, considering the impacts from coarse and fine aggregates, cement, fly ash, GGBFS, admixtures, concrete mixing, transportation, and placement processes. The results indicated that replacing 40% of Portland cement with GGBFS in the production of 25 MPa or 32 MPa concrete can result in a 22% reduction in CO₂ emissions. It is estimated that global production of GGBFS and steel slag in the previous year ranged from 260–330 million tons and 150–220 million tons, respectively [10].

2. EXPERIMENTAL DETAILS

2.1. Materials

The materials used in this study include 1).Type I Portland Cement, which has no special properties and refers to ASTM C150-83a standards; the brand used is Semen Tiga Roda. 2).The fine aggregate is concrete sand sourced from the Galunggung area, The test result in Table 1. 3).The coarse aggregate used is crushed stone with a nominal size of 19–20 mm, with detailed characteristics presented in the Table 1. 4).The mixing water was obtained from the Structural Laboratory at the Faculty of Technology and Vocational Education, Universitas Pendidikan Indonesia, which appeared clear and odorless. 5).The Ground Granulated Blast Furnace Slag (GGBFS) used in this research was supplied by PT Krakatau Semen Indonesia, Cilegon. GGBFS is white in color and has finer particles compared to Ordinary Portland Cement (OPC), resulting in lower concrete permeability. Based on the specific gravity test, the GGBFS used had a specific gravity of 2.91. The complete physical and chemical properties of the GGBFS are detailed in Table 2 and 3.

Table 1: Summary of Fine and Coarse Aggregate Material Test Results

Fine Aggregate			Coarse Aggregate		
1	Moisture Content	2.11	1	Moisture Content	549%
2	Bulk Density	1467	2	Bulk Density	1540 kg/m ³
3	Fineness Modulus	2.86	3	Aggregate Abrasion	26.44%
4	Silt Content	5.88	4	Apparent Specific Gravity	2.22
5	Apparent Specific Gravity	2.38	5	Bulk Specific Gravity (Oven-Dry)	2.33
6	Bulk Specific Gravity (Oven-Dry)	2.55	6	Bulk Specific Gravity (SSD)	2.48
7	Bulk Specific Gravity (SSD)	2.85	7	Water Absorption	4.62%
8	Water Absorption	6.84			

Table 2: Physical Properties of GGBFS

Parameter	Unit	Standard
Specific Gravity	–	2.5–2.9
Water Absorption	%	1.2
Fineness Modulus	cm ² /g	2.76
Surface Area	cm ² /g	4250–4700
Bulk Density	kg/m ³	1555

Table 3: Chemical Properties of GGBFS

Parameter	Unit	Req	Standard	Protocol
Alumunium Trioxide (Al ₂ O ₃)	%	max	16	ASTM C 114
Calcium Oxide (CaO)	%	min	37	ASTM C 114
Magnesium Oxide (MgO)	%	max	10	ASTM C 114
Silicon Dioxide (SiO ₂)	%	max	40	ASTM C 114
Chloride (Cl)	%	max	0,1	ASTM C 114
Loss On ignition (Lol)	%	max	3	ASTM C 114
Glass Content (Glass)	%	min	97	ASTM C 114
Strenght Activity (3 days)	%	min	45	ASTM C 109
Strenght Activity (7 days)	%	min	70	ASTM C 109
Strenght Activity (28 days)	%	min	95	ASTM C 109

2.2. Mix Design

A total of 60 samples were used in this study. The number of samples was determined based on the variation in the substitution of Ground Granulated Blast Furnace Slag (GGBFS) for Ordinary Portland Cement (OPC), as well as the number of testing days. The substitution variations used in this research were as follows: 0%, 20%, 40%, 50%, 60%, and 80%. For ease of reference, the following notation was applied to the concrete specimens: BN for Normal Concrete and BGG BFS for Concrete with Ground Granulated Blast Furnace Slag substitution. The detail of specimen in Table 4.

Table 4: Classification and Number of Compressive Strength Tests and Samples

Classification	7 Days	14 Days	28 Days	56 Days	Total Samples
BN	3	3	3	3	12
BGG BFS 20%	3	3	3	3	12
BGG BFS 40%	3	3	3	3	12
BGG BFS 50%	3	3	3	3	12
BGG BFS 60%	3	3	3	3	12
BGG BFS 80%	3	3	3	3	12
Total					72

The concrete mix was designed for a target compressive strength ($f'c$) of 30 MPa using the American Concrete Institute (ACI) method [22]. The water–cement ratio (w/c) was set at 0.37. Based on the mix design calculations, the proportions of the concrete mixture per cubic meter (m^3) were determined as follows table 5.

Table 5: Mix Design Specimens per m^3

Mix	BN	BGG BFS 20%	BGG BFS 40%	BGG BFS 50%	BGG BFS 60%	BGG BFS 80%
GGBFS (Kg/ m^3)		104,02	208,04	260,05	312,06	416,08
Cement (Kg/ m^3)	554,05	443,24	332,43	277,03	221,62	110,81
Fine Aggregate (Kg/ m^3)	537,93	537,93	537,93	537,93	537,93	537,93
Coarse Aggregate (Kg/ m^3)	954,80	954,80	954,80	954,80	954,80	954,80
Water (Kg/ m^3)	205,00	205,00	205,00	205,00	205,00	205,00

2.3. Specimens Preparation and Testing

After determining the mix constituents, the next procedure involved preparing each material according to the target weight in separate containers. The mixing process was initiated by placing the coarse and fine aggregates into the concrete mixer, followed by mixing for approximately 2 minutes. Subsequently, cement was added to the aggregate mixture, and the dry mixing process was continued to achieve a uniform distribution of cement and aggregates. For the concrete mixtures containing Ground Granulated Blast Furnace Slag (GGBFS), the GGBFS and cement were first dry-mixed in a separate container (bucket) until homogenous, and then added into the mixer. The total amount of water was gradually introduced into the mixer during the 4th or 5th minute of mixing. The mixing process continued until the fresh concrete reached a uniform consistency. A container was placed in front of the mixer to receive the concrete mix. After 6 to 7 minutes of mixing and once the concrete appeared homogeneous, the fresh concrete was discharged into the container by tilting the mixer. A slump test was conducted immediately after mixing to assess workability. The concrete was then cast into cylindrical molds measuring 10 cm in diameter and 20 cm in height and left to set for 24 hours.

After demolding, the specimens underwent curing to ensure uninterrupted hydration. Proper curing is essential to prevent early-age cracking caused by rapid moisture loss. Curing was carried out for a minimum of seven days. For high early-strength concrete, curing was maintained for at least three days and kept in a continuously moist condition, unless accelerated curing methods were applied. Compressive strength tests were conducted at the concrete ages of 7, 14, 28, and 56 days using a Universal Testing Machine (UTM) with a capacity of 300 kN and an accuracy of 1 kN.

2.4. Analysis of Test Results

The data analysis in this study includes both the compressive strength of concrete and the calculation of emissions. The data will be analyzed and presented using a descriptive quantitative approach, supported by tables and graphical representations. These results will then be compared to identify the most effective concrete mix proportion.

The analysis of concrete emissions is divided into two main components: energy consumption and carbon emission calculations. The following steps outline the procedures used to analyze energy use and carbon emissions for each

concrete mix proportion per cubic meter (m³): a). Calculating the energy consumption and carbon emissions of each material in every mix design by multiplying the quantity of each material per cubic meter (m³) by its respective energy coefficient (GJ/m³) and emission coefficient (t-CO₂/m³) in Fig 1. b). Determining the total energy consumption and total carbon emissions for each mix by summing the contributions of all individual materials. c). Calculating the energy and emission intensity per unit of compressive strength (per MPa) by dividing the total energy and total emissions by the achieved compressive strength (MPa).

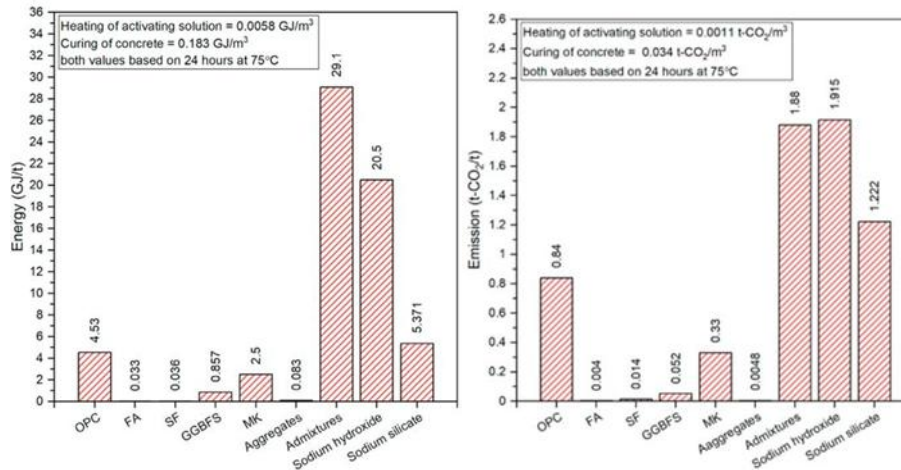


Figure 1. Energy and Carbon Emission Calculation Coefficients

Source: The Concrete Centre, 2009 & European Federation of Concrete, 2015 [23,24]

3. RESULTS AND DISCUSSION

3.1. Workability

Based on the concrete specimen preparation carried out using a constant water–cement ratio (w/c) in accordance with the control mix design, a workability test was performed using the slump test method for each casting of the various GGBFS substitution levels. The slump values obtained for each variation are presented in Table 6.

Table 6: Effect of GGBFS Substitution Percentage on Slump Value

No	Description	Substitution (%)	Slump Value (cm)
1	BN	0	3.0
2	BGGBFS 20%	20	5.5
3	BGGBFS 40%	40	6.5
4	BGGBFS 50%	50	7.0
5	BGGBFS 60%	60	7.5
6	BGGBFS 80%	80	9.0

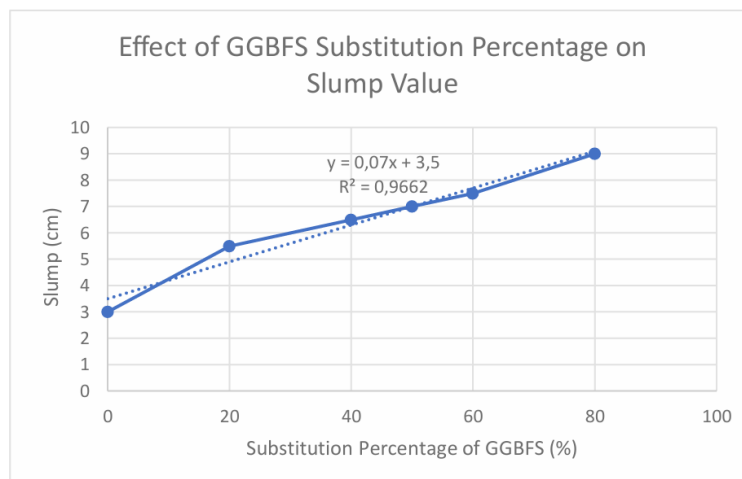


Figure 2. Effect of GGBFS Substitution Percentage on Slump Value

Based on Table 6 and Fig 2, it can be observed that the slump values vary across each experimental concrete variation. As the percentage of GGBFS substitution increases, the corresponding slump value also increases. This phenomenon can be attributed to the finer particle size of GGBFS and its lower initial water demand compared to Ordinary Portland Cement (OPC), due to its slower hydration reaction. Additionally, GGBFS has a lower water absorption rate of approximately 1.2%, compared to 1.5% for OPC—a difference of 0.3%. As a result, replacing OPC with GGBFS at a constant water–cement ratio leads to a more fluid concrete mix. This enhances the flowability and results in improved workability.

3.2. Analysis of Compressive Strength Test Results

The following are the results of the compressive strength tests for all concrete variations at the ages of 7, 14, 28, and 56 days.

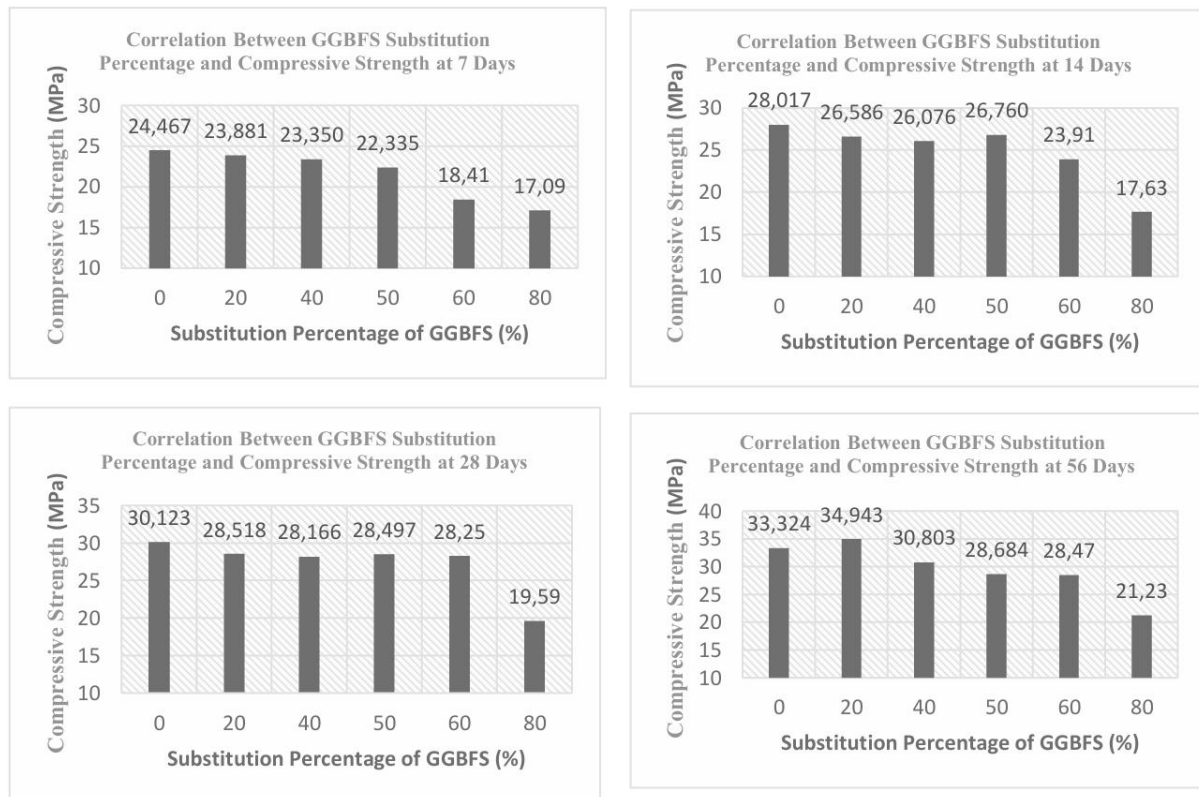


Figure 3. Correlation Between GGBFS Substitution Percentage and Compressive Strength

At 7 days of age, it can be concluded that the highest compressive strength was observed in the Normal Concrete (BN) at 24.467 MPa, while the lowest was recorded in BGGFBFS 80% at 17.09 MPa. The compressive strength showed a gradual decline from BN to BGGFBFS 80%, with the most significant decrease occurring between BGGFBFS 50% and BGGFBFS 60%, amounting to 17.57%. At 14 days, the highest compressive strength was again recorded in Normal Concrete (BN), reaching 28.017 MPa. The strength values at this age exhibited a fluctuating pattern. From BN to BGGFBFS 40%, a decrease of 6.93% was observed, with BGGFBFS 40% achieving 26.076 MPa. A slight increase occurred at BGGFBFS 50%, with compressive strength rising by 2.62% to 26.760 MPa. However, strength declined sharply afterward, reaching 17.63 MPa at BGGFBFS 80%, representing a 34.13% reduction. This fluctuation may be attributed to inconsistent curing temperatures, which could have resulted in incomplete hydration throughout the concrete specimens.

At 28 days, the compressive strength graph indicates that only BN achieved the target design strength of 30 MPa, with a measured value of 30.123 MPa. Concrete mixes with GGBFS substitutions ranging from 20% to 60% exhibited a slight reduction in strength, averaging about 1.5 MPa below the target value. The average compressive strength for BGGFBFS 20% to BGGFBFS 60% was 28.359 MPa. In contrast, BGGFBFS 80% showed a significant reduction of 10.5 MPa below the target, achieving a compressive strength of only 19.59 MPa. According to Figure 3, at 56 days, the mixes that met or exceeded the target strength of 30 MPa were BN, BGGFBFS 20%, and BGGFBFS 40%. BGGFBFS 20% showed an increase of 4.85%, reaching 34.943 MPa. From BGGFBFS 40% to BGGFBFS 60%,

compressive strength gradually decreased: BGG BFS 40% at 30.803 MPa, BGG BFS 50% at 28.684 MPa, and BGG BFS 60% at 28.470 MPa. BGG BFS 80% experienced a more pronounced reduction in strength, dropping to 21.23 MPa.

Table 7: Summary of Compressive Strength Test Results

No	Days	Average of Compressive Strength (MPa)					
		0	20	40	50	60	80
1	7	24,467	23,881	23,350	22,335	18,412	17,087
2	14	28,017	26,586	26,076	26,760	23,907	17,626
3	28	30,123	28,518	28,166	28,497	28,255	19,592
4	56	33,324	34,943	30,803	28,684	28,471	21,227

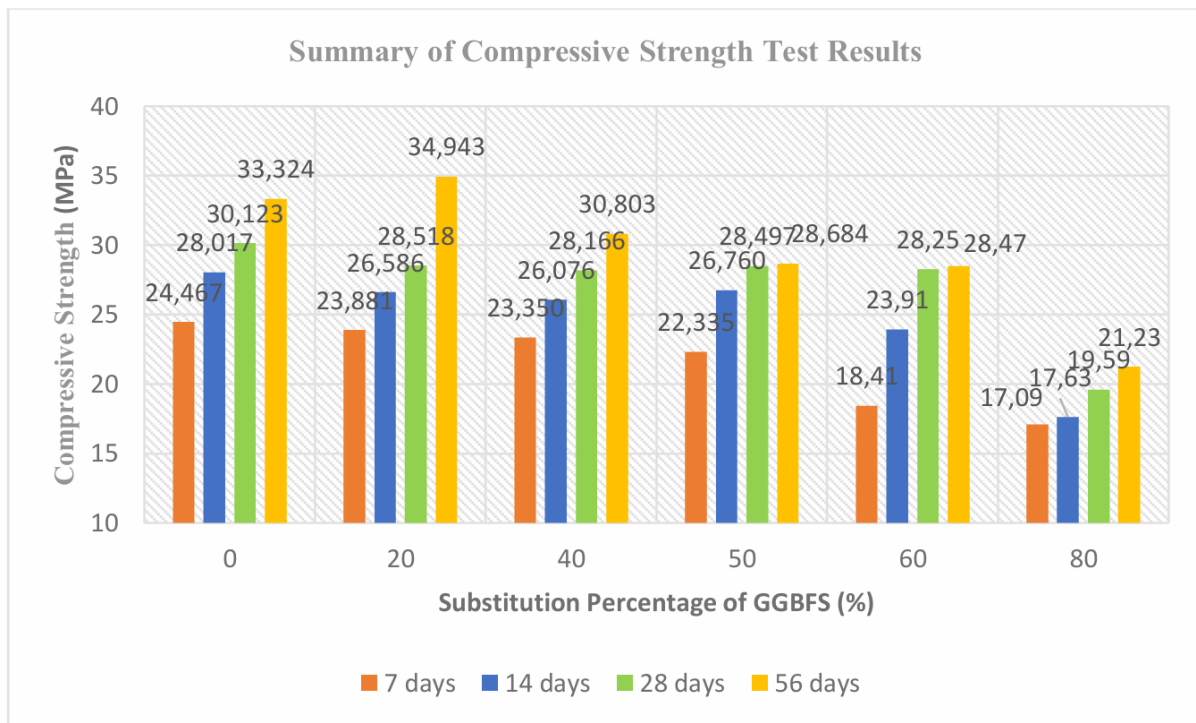


Figure 4. Summary of Compressive Strength Test Results

The average compressive strength summary graph shows that both normal concrete (BN) and GGBFS- substituted concrete (BGG BFS 20% to 80%) exhibited an increase in strength with age up to 56 days. At 28 days, only BN reached the target design strength of 30 MPa. However, at 56 days, BGG BFS 20% surpassed the compressive strength of BN with an increase of 4.85%. Additionally, BGG BFS 40% achieved the target strength at 56 days with a compressive strength of 30.803 MPa.

The increase in compressive strength of BGG BFS 20% can be attributed to two main factors. First, from a mechanical perspective, GGBFS has finer particles compared to Ordinary Portland Cement (OPC), with a particle size range of 325–400 mesh, while OPC typically reaches only 200 mesh. The finer particle size of GGBFS contributes to lower concrete permeability and denser pore structure, resulting in improved strength.

Second, GGBFS contributes to a stronger chemical bond during the hydration process alongside OPC. The primary reaction of OPC produces calcium silicate hydrate (C₃S₂H₃) and releases calcium hydroxide (Ca(OH)₂). When GGBFS is added, it utilizes the hydroxide ions (OH⁻) from Ca(OH)₂ as an activator, leading to the formation of additional calcium silicate hydrate (C-S-H) gel. This enhanced C-S-H formation results in denser and stronger concrete. GGBFS also exhibits carbon absorption capacity, with CaO as its main chemical component.

The strength gain observed at 56 days is due to the slower reaction rate of GGBFS compared to OPC. Unlike OPC, which reacts immediately with water, GGBFS requires calcium hydroxide from OPC hydration to initiate its own reaction. As a result, the early formation of C-S-H gel is delayed, but continues gradually over time. C-S-H plays a critical role in developing the compressive strength of concrete. Although slower, the hydration reaction

of GGBFS is more stable over time, allowing BGGFBS 50% to potentially reach the target design strength of 30 MPa at a later age. This is supported by the findings of Santosh Kumar Karri, who reported that concrete with 50% GGBFS substitution can still achieve the design strength (e.g., 20 or 40 MPa) at 90 days. However, BGGFBS 60% and 80% are unlikely to reach the target strength. This assumption aligns with the study conducted by Maitri Mapa, which found that substituting OPC with 60% and 80% GGBFS had a negative effect on compressive strength at all tested ages. A strength reduction of approximately 28.11% from the target value was observed, even at 90 days. This decline is likely due to the exhaustion of hydroxide ions (OH^-) from $\text{Ca}(\text{OH})_2$, which limits further C-S-H formation, thus halting strength development before the target is reached.

3.3. Energy and Carbon Emission Analysis

The following presents the results of the energy and carbon emission analysis for each variation of GGBFS substitution percentage in table 8.

Table 8: Summary of Energy and Carbon Emission Analysis

No	Description	Substitution Percentage of GGBFS (%)					
		0	20	40	50	60	80
1	Energy (GJ/m ³)	2633,76	2251,70	1869,64	1678,61	1487,57	1105,51
2	Carbon Emissions (t-CO ₂ /m ³)	472,57	390,60	308,64	267,65	226,67	144,70

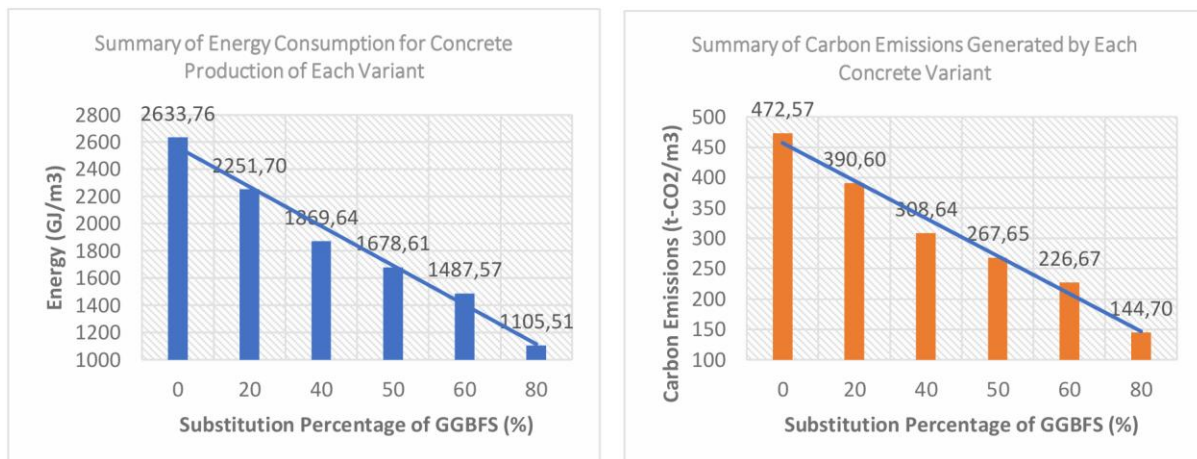


Figure 5. Summary of Energy and Carbon Emission Analysis

Based on Figure 5, it can be concluded that the higher the percentage of GGBFS substitution, the lower the total energy consumption in concrete production. According to data from The Concrete Centre and the European Federation of Concrete (2015), the energy coefficient for Ordinary Portland Cement (OPC) is 4.53, whereas for Ground Granulated Blast Furnace Slag (GGBFS) it is only 0.857. This significant difference is attributed to the manufacturing process of OPC, which requires large quantities of natural raw materials such as limestone, clay, and gypsum, along with high energy consumption during clinker production, which involves extreme heating. In contrast, GGBFS is a recycled by-product from the steel manufacturing industry, which contributes to reducing industrial waste. As a result, substituting OPC with GGBFS leads to a more energy - efficient and environmentally friendly concrete mix.

Furthermore, Fig 5 also demonstrates that increasing the percentage of GGBFS substitution results in a lower carbon emission impact from the concrete. As reported by The Concrete Centre and the European Federation of Concrete (2015), the carbon emission coefficient for OPC is approximately 0.84, while for GGBFS it is only 0.052. The production of OPC is one of the largest contributors to global carbon emissions—accounting for nearly 8% mainly due to the clinkerization process, which requires heating at temperatures between 1300°C and 1450°C, generating substantial amounts of carbon dioxide. GGBFS, on the other hand, is a by-product of iron ore processing and has the ability to absorb carbon, both during activation and once incorporated into hardened concrete. This characteristic makes GGBFS a more sustainable material choice, not only reducing energy consumption but also mitigating the carbon footprint of cementitious composites.

3.4. Correlation Between Concrete Compressive Strength and Energy–Carbon Emission Analysis

This section discusses the research findings regarding the relationship between the compressive strength of concrete and the associated energy consumption and carbon emissions.

Table 9: The Correlation Between Concrete Compressive Strength and Energy and Carbon Emission Analysis

No	Description	GGBFS Substitution (%)	Total Energy (GJ/m ³)	Total Emissions (t-CO ₂ /m ³)	Average Compressive Strength at 56 Days (MPa)
1	BN	0	2633,76	472,57	33,324
2	BGGBFS 20%	20	2251,70	390,60	34,943
3	BGGBFS 40%	40	1869,64	308,64	30,803
4	BGGBFS 50%	50	1678,61	267,65	28,684
5	BGGBFS 60%	60	1487,57	226,67	28,471
6	BGGBFS 80%	80	1105,51	144,70	21,227

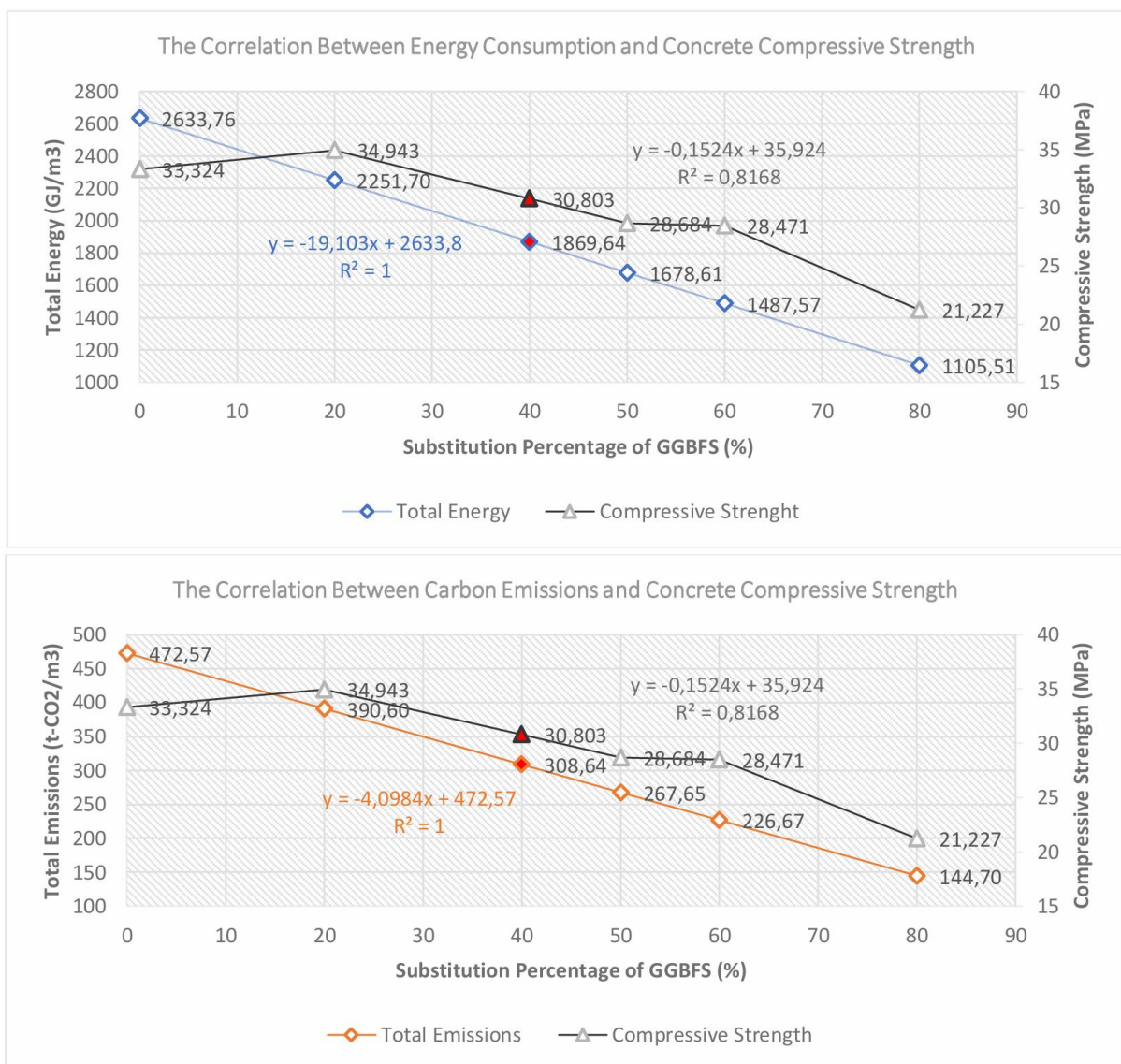


Figure 6. Correlation Between Concrete Compressive Strength and Energy and Carbon Emission Analysis

Fig 6, which illustrates the relationship between energy consumption and compressive strength of concrete, shows that a general trend exists: the lower the energy consumption, the lower the compressive strength. However, an exception is observed with the BGG BFS 20% mix, which demonstrates higher compressive strength despite reduced energy usage. Similarly, the correlation between carbon emissions and compressive strength reveals a comparable pattern—lower emissions generally lead to reduced compressive strength, with the exception again being the BGG BFS 20% mix.

Concrete incorporating GGBFS as a partial substitute for OPC presents a more environmentally friendly alternative to conventional concrete. As observed in Table 9, both the BGG BFS 20% and BGG BFS 40% mixes reach the target strength of 30 MPa, albeit at a slower rate compared to concrete made with 100% OPC. These findings highlight the potential of GGBFS substitution as a strategy for industrial waste reuse, energy conservation, natural resource preservation, and significant reduction of carbon emissions associated with OPC production. Based on the results of this study, the optimal substitution percentage of GGBFS for OPC—taking into account compressive strength, energy consumption, and carbon emissions—is identified as 40%. The BGG BFS 40% mix achieved a compressive strength of 30.803 MPa at 56 days, meeting the 30 MPa target. Although it did not meet the target at 28 days, the shortfall was only approximately ± 2 MPa below the design strength.

In terms of environmental benefits, the BGG BFS 40% mix reduced energy consumption by 765.12 GJ/m³ and carbon emissions by 163.93 t-CO₂/m³ compared to the control mix (BN) targeting 30 MPa. According to the Indonesian Ministry of Environment and Forestry (KLHK) and the U.S. Environmental Protection Agency (EPA), a single tree can absorb an average of 21 kg of CO₂ per year. Thus, the emission reduction achieved by substituting 40% GGBFS in concrete is equivalent to planting approximately 7,810 trees over the course of one year.

4. CONCLUSIONS

Based on the research findings, calculations, and analysis conducted, the following conclusions can be drawn:

- 1) The compressive strength of concrete at 56 days increased by 4.85% with a 20% GGBFS substitution, followed by a successive decrease at 40%, 50%, 60%, and 80% substitution levels by 11.84%, 6.87%, 0.74%, and 25.44%, respectively, compared to the control mix.
- 2) The reduction in carbon emissions achieved through GGBFS substitution at 20%, 40%, 50%, 60%, and 80% compared to normal concrete (BN) was 17.34%, 34.68%, 43.36%, 52.03%, and 69.37%, respectively.
- 3) The optimal substitution percentage of GGBFS with respect to maintaining compressive strength, minimizing energy consumption, and reducing carbon emissions is identified as 40%. At this level, the concrete achieved an average compressive strength of 30.803 MPa at 56 days, with associated energy consumption and carbon emissions of 1869.64 GJ/m³ and 308.64 t-CO₂/m³, respectively.

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