DEVELOPMENT OF FLY ASH AND STEEL SLAG-BASED GEOPOLYMER CONCRETE TO REDUCE CARBON EMISSIONS IN CONSTRUCTION

Yehezkiel Septian Yoganata[1,*], Ikhsan Putra Pratama[1], Najla Nurrahma Amalia[1], Mohammad Amru Bil Ihsani[1], Kharisma Nur Cahyani[1], Nur Laily Lupita Sari[1]

[1] Civil Engineering Department, Politeknik Negeri Malang
Jl. Soekarno-Hatta, No. 9, Jatimulyo, Kec. Lowokwaru, Kota Malang,
Jawa Timur 65141
[*]Correspondent Author: yehezkielseptian@polinema.ac.id

Abstract
The global construction sector, particularly the production of concrete structures, is a major contributor to carbon dioxide (CO_2) emissions. Portland cement alone is responsible for 10% of global emissions. In response to this sustainability issue, this research aims to develop green concrete through the partial substitution of cement using fly ash and fine aggregate with steel slag, based on the similarity of the chemical composition of these industrial wastes to concrete materials. The research focuses on two objectives: producing a concrete mix formula that meets the compressive strength standard of 21 MPa and comparing CO_2 emissions level. The experiment was conducted in the laboratory in accordance with SNI 7656:2012, involving the fabrication of 24 cylindrical test specimens with three variations of fly ash substitution (10%, 15%, 20%) and steel slag substitution (20%, 15%, 10%). The 28-day compressive strength test results showed that all variations exceeded the strength of conventional concrete (22.29 MPa). Specifically, Variation II (15% fly ash, 15% steel slag) achieved optimal performance with a compressive strength of 24.91 MPa. In addition to its mechanical advantages, this optimal variation also reduced carbon emissions by 15%. These findings highlight the great potential of utilizing industrial waste in producing strong and environmentally friendly concrete.

Keywords: *compressive strength, CO_2 emissions, fly ash, green concrete, steel slag*

INTRODUCTION

Concrete is the most commonly used construction material. Almost all construction uses concrete, such as buildings, bridges, roads, water structures, and etc. (Pangestu & Sudjatmiko, 2021). Concrete is a composite material composed of cement which acts as a binder, coarse aggregate and fine aggregate as filler materials, and water acts as a material to facilitate the workability process (Alrasyid et al., 2017). Portland cement is the main binding material of concrete due to its ability to form a hard bond through the process of hydration. Meanwhile, hydration is the process that produces calcium silicate hydrate (C-S-H) compounds, which can provide strength to the concrete (Fauziyyah & Zuraida, 2023). The compressive strength of concrete depends on the quality of the cement, the water-cement ratio used, and the type of fine and coarse aggregate used (Muharram & Walujodjati, 2022). This indicates that the variation in aggregate type significantly influences the mechanical characteristics of concrete, including compressive strength and workability, making the selection of aggregate an important factor in determining the overall performance of the concrete (Alani et al., 2025).

Green concrete is an environmentally friendly concrete designed to reduce environmental impact and high emissions during its life cycle. It has a purpose to maximize the use of waste or recycled materials while maintaining or improving the mechanical properties of conventional concrete (Pangestu & Sudjatmiko, 2021). In line with that, using industrial waste in the production of green concrete can reduce carbon without compromising the concrete's mechanical performance (Habert et al., 2011).

Construction contributes significantly to the increase in the level of carbon dioxide (CO_2) emissions worldwide, particularly in the production of building materials such as cement. Portland cement is the biggest contributor to carbon emissions generated in the production of concrete (Turner & Collins, 2013). The production of cement requires a high-temperature process to heat the carbon-containing raw materials, with temperatures that can reach up to 1450^0C. This process produces a very large amount of carbon dioxide (CO_2). Currently, cement contributes up to 8-10% of the world's total carbon emissions (DarvishaliNezhad & Mousavinejad, 2025). The wastes that can currently be utilized are fly ash and steel slag. Fly ash is a waste material produced from the coal combustion process in steam power plants (PLTU). It possesses properties rich in silica (SiO_2), alumina (Al_2 O_3), and several other oxides with pozzolanic characteristics similar to cement, which serves as a binding material in concrete. Meanwhile, steel slag is a waste product generated from steel smelting that contains mineral characteristics similar to the aggregates used in concrete mixtures. (Zhao et al., 2025).

Partial substitution of cement and aggregate material with this industrial waste can reduce the use of cement. The utilization of this industrial waste is considered capable of suppressing the level of environmental pollution and also reducing the level of carbon emissions worldwide (Nurwidayati et al., 2024). In order to achieve this, an innovation in green concrete substitution is needed, utilizing a combination of industrial wastes, fly ash and steel slag, as a partial substitute for cement and aggregate in the concrete mixture. The main benefit of creating this innovation is to significantly reduce carbon dioxide (CO_2) emissions due to the reduced use of cement in the concrete mixture (Olii et al., 2023).

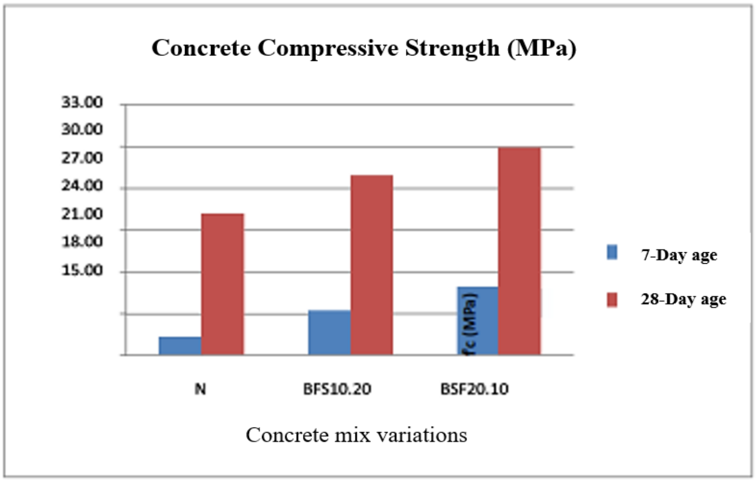

Figure 1. Concrete Compressive Strength Test Results Using Fly Ash and Steel Slag (Fitriadewi et al., 2024)

RESEARCH METHODS

The research was conducted experimentally in the laboratory using 24 cylindrical specimens measuring 15x30 cm. The compressive strength tests were carried out at 7 and 28 days. The following materials were used in this study:

1. Type I Portland cement (Semen Gresik)
2. Class C fly ash (waste product from the Paiton Steam Power Plant)
3. Steel slag (waste from steel smelting by Forza Nusantara Steel)
4. Standard coarse and fine aggregate (sand from Lumajang city)
5. Clean water for mixing

(a) (b) (c) (d)

Figure 1. The Materials (a) Coarse Aggregate (b) Fine Aggregate (c) Fly Ash (d) Steel Slag

The research stages began with designing the mix design for normal concrete variations (SNI-03-2834, 2002) followed by calculations for variation I (CV I), variation II (CV II), and variation III (CV III). The design of the concrete mix design was the initial stage in concrete production. The following are the parameters for the mix design.

After the concrete mix design was formulated based on the parameters in Table 1, the required concrete mix composition was obtained. Then, fly ash and steel slag would be used as replacement materials for cement and fine aggregate, respectively. Fly ash would replace cement by 10%, 15%, and 20%, and steel slag would replace fine aggregate by 20%, 15%, and 10%, resulting in four concrete variations with different cement and fine aggregate compositions.

Table 1. Concrete Mix Design Parameters

No	Parameter	Data
1	Target compressive strength, f'c (MPa)	21
2	Type of cement	Type I Portland cement (Semen Gresik)
3	Maximum size of coarse aggregate	20 mm
4	Type of fine aggregate	River sand
5	Type of coarse aggregate	Crushed stone
6	Water-Cement Ratio	0.6
7	Specific gravity of cement (g/cm³)	3.15
8	Specific gravity of sand (SSD) (g/cm³)	2.66
9	Specific gravity of gravel (SSD) (g/cm³)	2.616
10	Bulk density of gravel	1199.212
11	Moisture content of sand (%)	0.0106
12	Moisture content of gravel (%)	0.028
13	Sand absorption (%)	1.83
14	Gravel absorption (%)	2.35
15	Design slump (mm)	60-120
16	Admixture	None

Table 2. Proportions of the Entire Concrete Mixture Variation

Material	Concrete Variations			
	NC	CV I	CV II	CV III
Fly ash substitution (%)	0	10	15	20
Steel slag substitution (%)	0	20	15	10
Cement (kg)	13.13	11.82	11.16	10.51
Sand (kg)	16.98	13.58	14.43	15.28
Gravel (kg)	37.25	37.25	37.25	37.25
Water (kg)	7.24	7.24	7.24	7.24
Fly ash (kg)	0	1.31	1.97	2.63
Steel Slag (kg)	0	3.40	2.55	1.70

Note: NC (Normal Concrete), CV (Concrete Variation)

After determining the mix proportions to be used, the preparation of the test specimens was carried out through the following stages:

1. Measurement and weighing of material requirements
   Fly ash and steel slag were measured according to the concrete mix formulation, then weighed based on the mix requirements for each concrete variation.
2. Mixing materials according to concrete variations needs
   The materials were mixed using a 150-liter capacity mixer.
3. Slump test
   The slump test was conducted before discharging the concrete from the mixer. If the slump value met the design range (60-120 mm), then the concrete mixture proceeded to the molding stage.
4. Pouring of the concrete mixture into the cylindrical mold
   Fresh concrete mixture was poured into the cylindrical molds in layers. Each layer was compacted using a tamping rod or vibrator to eliminate air voids.
5. Demolding and preparation for curing
   After the mold was closed, the concrete was left for 24 hours at room temperature.
6. Curing of test specimens
   The demolded specimens were labeled according to their variation and then submerged in a specific curing tank.
7. Weighing the test specimens
   After the curing period, the specimens were removed from the curing tank and left at room temperature for 24 hours to ensure they were dry.
8. Capping process before compressive strength test
   Sulfur was heated to a certain temperature until melted and then poured into the circular capping mold.
9. Compressive strength test
   The capped specimens were tested using a compression using a compression testing machine. The tests were carried out at the concrete ages of 7 and 28 days.
10. Data analysis and discussion
    The analysis was carried out after the test results data were obtained.

Figure 2. Mixing Process

Gambar 3. Slump test

Figure 4. Cylinder Test Specimen

Figure 5. Curing of Test Specimens

Figure 6. Compressive Strength Test

RESULT AND DISCUSSION

After testing the concrete specimens, the results and data obtained were then analyzed and discussed as follows:

1. Analysis of Compressive Strength

   Based on the results of the concrete compressive strength test of cylindrical test specimens with a diameter of 15 cm and a height of 30 cm at 7 days and 28 days (SNI 1974: 2023, 2023). Three samples were made for each concrete mixture, and the test results are presented in Table 3 and Figure 6.

Table 3. Analysis of Concrete Compressive Strength Calculation

Specimen	Fly Ash Content	Steel Slag Content	Surface Area of the Cylinder	At 7 days			At 28 days		
				Max Load	Compression (f'c)	f'c (average)	Max Load	Compression (f'c)	f'c (average)
			(mm^2)	(N)	(MPa)	(MPa)	(N)	(MPa)	(MPa)
NC	0%	0%	17671.46	277000	15.67	12,92	374000	24.05	22.29
			17671.46	216000	12.22		338000	21.74	
			17671.46	192000	10.86		328000	21.09	
CV I	10%	20%	17671.46	381000	21.56	18,45	483000	31.06	22.31
			17671.46	308000	17.43		299000	19.23	
			17671.46	289000	16.35		259000	16.66	
CV II	15%	15%	17671.46	304000	17.20	18,62	333000	21.41	24.91
			17671.46	404000	22.86		512000	32.92	
			17671.46	279000	15.79		317000	20.38	
CV III	20%	10%	17671.46	242000	13.69	13,86	403000	25.91	22.79
			17671.46	260000	14.71		263000	16.91	
			17671.46	233000	13.19		397000	25.53	

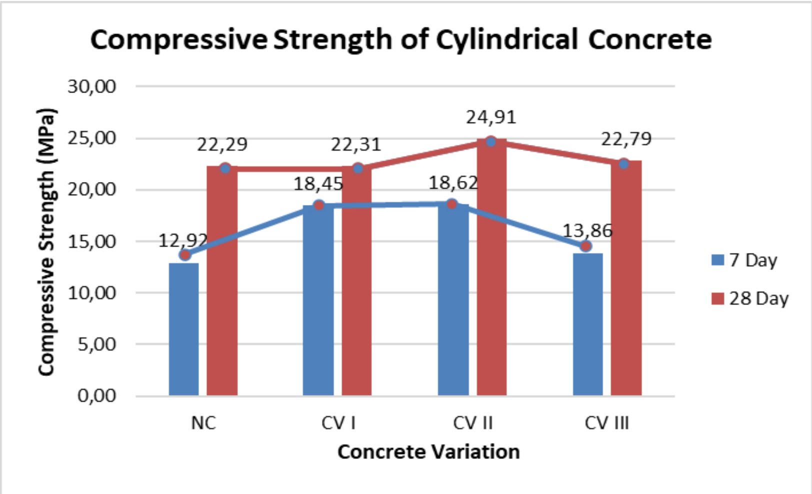

Figure 6. Compressive Strength Test Results for All Variations

Based on Table 3 and Figure 6, the average compressive strength of concrete for the four concrete variations was obtained. The average compressive strength of conventional concrete was 12.92 MPa at 7 days and 22.29 MPa at 28 days. Furthermore, the compressive strength of CV I was 18.45 MPa at 7 days and 22.31 MPa at 28 days. The average compressive strength of CV II was 18.62 MPa at 7 days and 24.91 MPa at 28 days. Finally, the average compressive strength of CV III was 13.86 MPa at 7 days and 22.79 MPa at 28 days. It can be seen that the highest and optimum average compressive strength was produced by CV II with a compressive strength of 24.91 MPa.

2. The highest compressive strength achieved by Variation CV II (24.91 MPa at 28 days) is due to its optimal additive composition, specifically 15% Fly Ash and 15% Steel Slag, which creates a dual synergistic effect. Chemically, Fly Ash participates in a pozzolanic reaction with Calcium Hydroxide (CH) from the cement, producing additional Calcium Silicate Hydrate (C-S-H), which serves as the main binder and increases long-term compressive strength. Steel Slag also contributes through its latent cementitious properties. Physically, the extremely fine Fly Ash particles act as a micro-filler or particle packing, filling micro-voids between the cement and aggregate materials. The combination of increased C-S-H (from chemical reactions) and reduced porosity (from particle packing) results in the densest, most homogeneous, and strongest concrete matrix among all tested variations.Analysis of Carbon Emission Rate. The analysis of the calculation for the efficiency of the carbon emission rate after the preparation of the test specimen is presented in Table 4.

Table 4. Results of Concrete Carbon Emission Calculation

Specimens	Fly ash content (%)	Cement content (%)	Cement content (kg)	CO_2 emissions per m^3 of concrete (kg CO_2 eqv)	Percentage decrease in content (%)
NC	0	100	13.13	12.35	0
CV I	10	90	11.82	11.11	10
CV II	15	85	11.16	10.49	15
CV III	20	80	10.51	9.88	20

According to Fauziyyah & Zuraida (2023), based on its specifications, 1 kg of Portland cement produces 0.94 kg of CO_2. Based on the tests that have been conducted, each concrete variation used a different amount of cement in its mixture due to the substitution of fly ash as the cement replacement at varying percentages for each variation. Normal concrete (NC) used 13.13 kg of cement, which resulted in 12.347 kg of CO_2. Concrete variation I (CV I) used 11.82 kg of cement and produced 11.11 kg of CO_2. Concrete variation II (CV II) used 11.16 kg of cement, resulting in 10.49 kg of CO_2. Concrete variation III (CV III) used 10.51 kg of cement, producing 9.88 kg of CO_2. When aligned with the highest concrete compressive strength achieved in variation II, a reduction in the CO_2 carbon emission level of 15% was obtained.

3. Analysis of Material Cost Efficiency
   The analysis of material cost efficiency calculation was based on the cost of producing the test specimens.

Table 5. Calculation of Material Volume

Description	Unit	NC	CV 1	CV II	CV III
Water	Lt	7.242	7.242	7.242	7.242
Sand	kg	16.976	13.581	14.430	15.279
Gravel	kg	37.249	37.249	37.249	37.249
Cement	kg	13.135	11.821	11.165	10.508
Fly Ash	kg	-	1.313	1.970	2.627
Steel Slag	kg	-	3.395	2.546	1.698

The calculations of material volume show that the variations of green concrete (CV I, CV II, and CV III) were achieved by reducing the volume of cement and sand, which were directly replaced by a combination of fly ash and steel slag. CV I was formulated with the highest proportion of steel slag, while CV III contained the highest proportion of fly ash. The objective was to test the impact of various combinations of waste materials on the properties of the concrete. Based on the volume calculations in Table 5, the subsequent cost calculations are presented in Table 6.

Based on Table 6, it can be concluded that the normal concrete (NC) had the highest total cost of Rp 755,210.21 due to the greater use of cement and sand, amounting to Rp 18,060.31 and Rp 59,417.74, respectively. In contrast, the green concrete mixtures, which partially replaced cement and sand with fly ash and steel slag, successfully reduced the total cost. CV I was the most economical formulation with a total cost of Rp 748,189.75, driven by the lowest sand cost of Rp 47,534.19 and the highest steel slag cost of Rp 5,092.95, which overall resulted in savings compared to normal concrete.

Table 6. Analysis of the Green Concrete Bill of Quantities Calculation

Description	Unit	NC (Rp)	CV I (Rp)	CV II (Rp)	CV III (Rp)
Water	Lt	7,242.09	7,242.09	7,242.09	7,242.08
Sand	kg	59,417.74	47,534.19	50,505.08	53,475.97
Gravel	kg	670,490.07	670,490.07	670,490.07	670,490.07
Cement	kg	18,060.31	16,234.28	15,351.26	14,448.24
Fly Ash	kg	-	1,576.17	2,364.26	3,152.34
Steel Slag	kg	-	5,092.95	3,819.71	2,546.48
Total	-	755,210.21	748,189.75	749,772.45	751,355.18

CONCLUSION

The compressive strength test results showed that all variations of green concrete (CV I, CV II, and CV III) achieved a significant increase in average compressive strength compared to conventional concrete (NC) at both 7 and 28 days. The most optimal compressive strength was achieved by Green Concrete Variation II (CV II), yielding a compressive strength of 24.91 MPa at 28 days, surpassing conventional concrete, which was only 22.29 MPa at the same age. CV II used an optimal substitution combination of 15% fly ash and 15% steel slag. Based on the emission calculations, all variations of green concrete successfully demonstrated a reduction in CO_2 emission levels compared to conventional concrete. Most notably, Green Concrete Variation II (CV II), which also achieved the highest compressive strength, was able to reduce carbon emissions by up to 15%. From a cost perspective, overall, all green concrete variations had lower production costs than conventional concrete. Therefore, based on the all the measured components, the CV II concrete variation is the best option.

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