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Reusing Coal Waste as a Blending Material for Hollow Block Production to Boost Circular Economic of FABA

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Abstract: In many parts of the world, including Indonesia, coal is the primary energy source for numerous steam power plants (PLTU) due to the depletion and rising costs of oil. Furthermore, given the abundance of coal resources, it remains the primary energy source for power plants in Indonesia. One significant advantage of using coal in power generation is its relatively high economic efficiency, typically at around 80%, which can be comparable to certain renewable sources like solar energy [1]. However, using coal reveals its negative aspects through its environmental impact and adverse effects on air quality. During the combustion of coal in power plants, it produces Fly ash and Bottom ash (FABA) containing various inorganic minerals that, when released into the environment, cause air and soil pollution. To align with established economic principles, the Construction and Demolition (C and D) sector should adopt a strategy that promotes materials and products with zero material value, ensuring zero residual waste generation during their circulation and final disposal [2]. Therefore, this research aimed to investigate the minimization of negative impacts caused by FABA produced by coal power plants on the environment using principles of the Circular Economy. Fly ash (FA), when mixed with water, will produce calcium silicate hydrate (cement compound). And Bottom Ash (BA), 90-100 percent passes the 4.75 mm sieve. The particle size, as well as its durability, is advantageous as a fine aggregate that can be used to fill pavement structures. The experiment was carried out using FABA from coal combustion as a blending material to make hollow blocks in six different sizes. The result showed that a higher FABA percentage promotes the production of a quality hollow block at a lower cost. An in-depth economic cost analysis showed that incorporating FABA as a blending material for hollow block production provided a 55% increase in economic benefits and a 34.67% improvement in the quality of a hollow block compared to the composition of materials without FABA mixture.

Keywords: FABA, hollow blocks, Circular Economy

1. Introduction

PLTU Bukit Asam is a power plant that mainly uses coal in power generation, generating Fly Ash and Bottom Ash (FABA) waste annually. The plant generates approximately 2,887 tonnes per day or 690,000 tonnes per year of FABA waste, along with other waste byproducts such as Coal Combustion Residues (CCRs). Unfortunately, these waste materials are currently being deposited in landfills for disposal.

According to Sharma (2020), it has been reported that the FABA from coal combustion can be used as partial replacements for cement or suitable aggregate substitutes in the manufacture of concrete. Additionally, Fly Ash (FA) can also be used to enhance the durability of concrete, including its sulfate resistance [3]. Converting coal ash into a "monolith" and stable compound involves mixing it with cement, and adding fillers such as sand, lime, or other right material. Consequently, using FABA in concrete production can result in higher quality and cost-effective concrete [4][5][6].

The percentage of fa generated based on the weight of the treated waste ranges between 3% to 4%, while the proportion of bottom ash (ba) can reach around 20%. Therefore, it is important to further reuse these byproducts and find sustainable final disposal to protect the environment [7]. Concrete is a structural material composed of fine aggregate (sand) and coarse aggregate (gravel), which are bonded together by water and portland cement or other similar hydraulic binders. This mixture may contain additional additives and should be made according to the standards outlined in the indonesian national standards (sni 1847:2013).

As a building material, concrete provides several advantages, including withstanding forces, and resisting weather fluctuations, and high temperatures due to its robust structural integrity. It is also malleable, which allows for convenient shaping to meet various needs. Besides concrete, another building material that plays an important role in modern construction is hollow blocks. In most cases, they are used as a substitute for bricks to construct walls and provide insulation. Hollow block has a less dense composition than solid block, giving a lower compressive strength.

The hollow block is made using smaller proportions of cement, and it has a bigger market share than a solid massive block.

Fly ash (FA) contains silica and alumina, is pozzolanic, and will react with calcium hydroxide. When mixed with water it will produce calcium silicate hydrate (cement compound). Its lime-binding ability makes it possible to replace Portland cement in concrete products. Meanwhile, Bottom Ash (BA) is bottom ash that has undergone vitrification, in the form of a coarse, hard, black, angular, glass-like material, mostly single in size with 90-100 percent passing a 4.75 mm sieve. The particle size, as well as its durability, is advantageous as a fine aggregate that can be used to fill pavement structures.

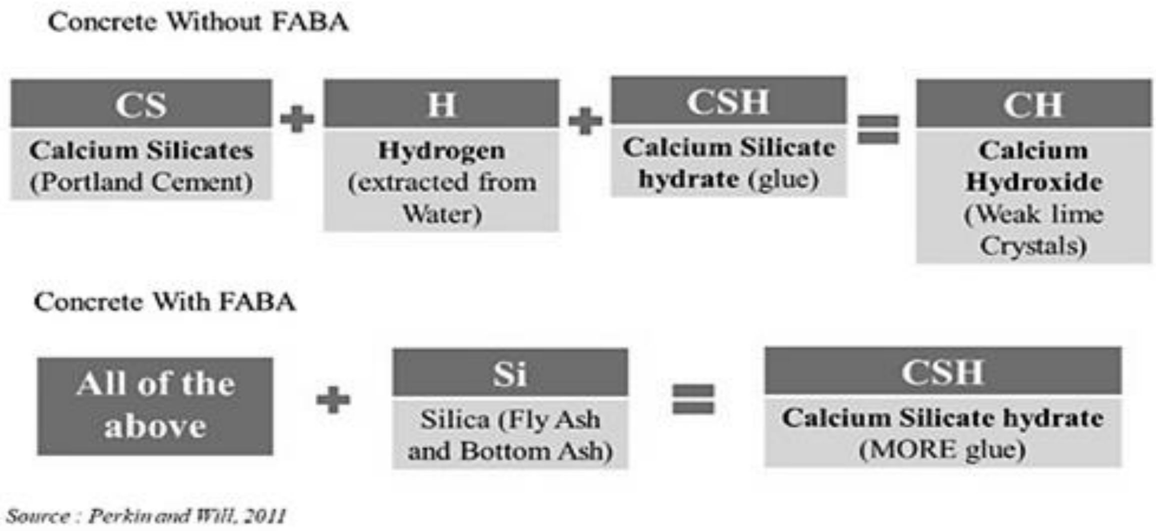

Figure 1. Utilization of Coal FA for Better and Environmentally Friendly Construction Quality

According to the experiment conducted [8], replacing BA with fine aggregate in concrete mixtures increased compressive strength. The most significant improvements were observed at replacement levels ranging from 0% to 15% at both the early age of 7 days and the age of 28 days. The compressive strength of the bottom ash began to decrease when the percentage of the mixture was increased to above 20%. However, the compressive strength of the bottom ash began to decrease when the percentage of the mixture was increased to above 20%. Furthermore, the level of water absorption began to increase in the mixture with a 20% replacement ratio of the material. It is concluded that the concrete mixture containing 10% and 15% Fly Ash has the maximum compressive strength. Conversely, water demand increases with the increasing levels of replacement of sand with BA [9]. This increase in water demand is attributed to the high porosity of BA, which absorbs water, leading to a higher water requirement. Similar results have been found in studies involving concrete made with bottom ash as sand, as reported by Kadam and Patil [10]. It is important to note that the density of concrete decreases with an increase in the percentage of replacement of BA from 0% to 30% due to the low specific gravity of bottom ash compared to fine aggregate.

2. Material and Methods

2.1. Research Design

In this research, the objective was to create a composite material suitable for producing a hollow block. To achieve this, a portion of the cement material was replaced with FABA during the hollow block production process. The hollow block was designed to have dimensions of 200 x 100 x 400 mm. To create the composite mixture, the research involved mixing 1 m^3 of sand with 6 sacks of cement. For reference, 1 m^3 of sand weighs approximately 1400 kg, and each sack of cement weighs 50 kg.

Mixed Composition:

(Sand/((Σ Sand+Cement)) x 100) equal to the percentage of sand or 82% sand, and

(Cement/((Σ sand+Cement)) x 100) equal to the percentage of cement or 18% Cement.

Approximately 5-30% of the original 18% cement was replaced by FABA, involving experimentation with six different mixed compositions and one control group without any mixture for comparison. The details are presented in Table 1.

Table 1. Comparative Analysis of Material for Hollow Block Production

Group	Sand (82 %)	Cement 18 %	*Fly ash* (%)	*Bottom ash* (%)
Control Group (K0, Not Mixed)	82	100	0	0
Group 1 (G1)	82	95	5	0
Group 2 (G2)	82	95	0	5
Group 3 (G3)	82	90	5	5
Group 4 (G4)	82	85	7.5	7.5
Group 5 (G5)	82	80	10	10
Group 6 (G6)	82	70	15	15

The drying time in the experiment used the following composition[11] : (a) 3 days; (b) 7 days; (c) 14 days; (d) 21 days; and (e) 28 days. The acquired data was investigated through statistical analysis using the ANOVA and LSD methods to determine whether there were any interaction effects between several variables as follows:

a. Relationship between the composition of the FA content in the hollow block and the compressive strength.
b. Correlation between hollow block product drying duration and compressive strength.
c. The economic evaluation of hollow block products was conducted for all six different mixed compositions of the hollow block mixture using FABA percentages of 15%, 20%, 25% and 30% is expected to produce a compressive strength of > 14.32 MPa and compressive strength tests were carried out when the hollow concrete bricks were 7, 14, 21 and 28 days old.

3. Results and Discussion

3.1. Dimensional Size

The results from the dimensional measurements, including the diameter, cross-sectional area, and compressive force, show that the hollow block used as a control does not exhibit any deviations in size, maintaining a diameter of 150 mm and a cross-sectional area of 17,671.46 mm^2. These measurements also remain within the agreed-upon requirements, falling below the tolerance limit allowed (+3 mm and -3 mm) established in the standard (SNI). This alignment is supported by the results of the compressive strength test, as shown in Figure 2.

Figure 2 shows that the size dimensions of hollow block products of different compositions are below the allowed tolerance value. FABA replacement, ranging between 5% and 30% of the cement's weight does not affect the dimensions of hollow block produced because FABA has a fairly fine size and granules compared to cement. Coal ash, which includes both FABA is finer and smaller than cement grains, making it easy to fill in the voids between aggregate grains and minimize existing pores [12]. Therefore, the replacement of coal ash with FABA does not significantly affect the dimensions of the produced hollow block product.

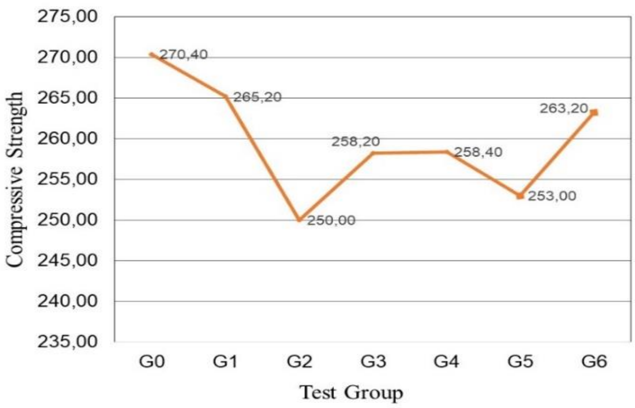

Figure 2. Compressive strength test results for each group of mixed composition

3.2. Compressive Strength

3.2.1. Correlation between Hollow Block Compressive Strength and Drying Age

Compressive strength is the ability of hollow block products to withstand broad unit compressive forces, which determines the quality of the hollow block product. For instance, the greater of compressive strength value, the higher of hollow block product quality. The compressive strength of hollow block products increases as the drying period increases.

Figure 3 shows that the compressive strength of the hollow block increases as the drying period increases. Based on these results, the control hollow block increases rapidly at the initial drying period of 7 days or 1 week of 15.11 MPa and slows down in weeks 2 and 3, namely 15.18 MPa and 15.27 MPa. After a drying period of 21 days and 28 days, the compressive strength increased to 15.42 MPa and 15.56 MPa.

The results indicated that the average compressive strength of the hollow block product increased significantly after a drying period of 14 days. During the initial drying period of 7 days, the hydration process of the hollow block product is still ongoing. After the age of 21 days, the compressive strength of the hollow block product will continue to increase and reach a maximum by the age of 28 days.

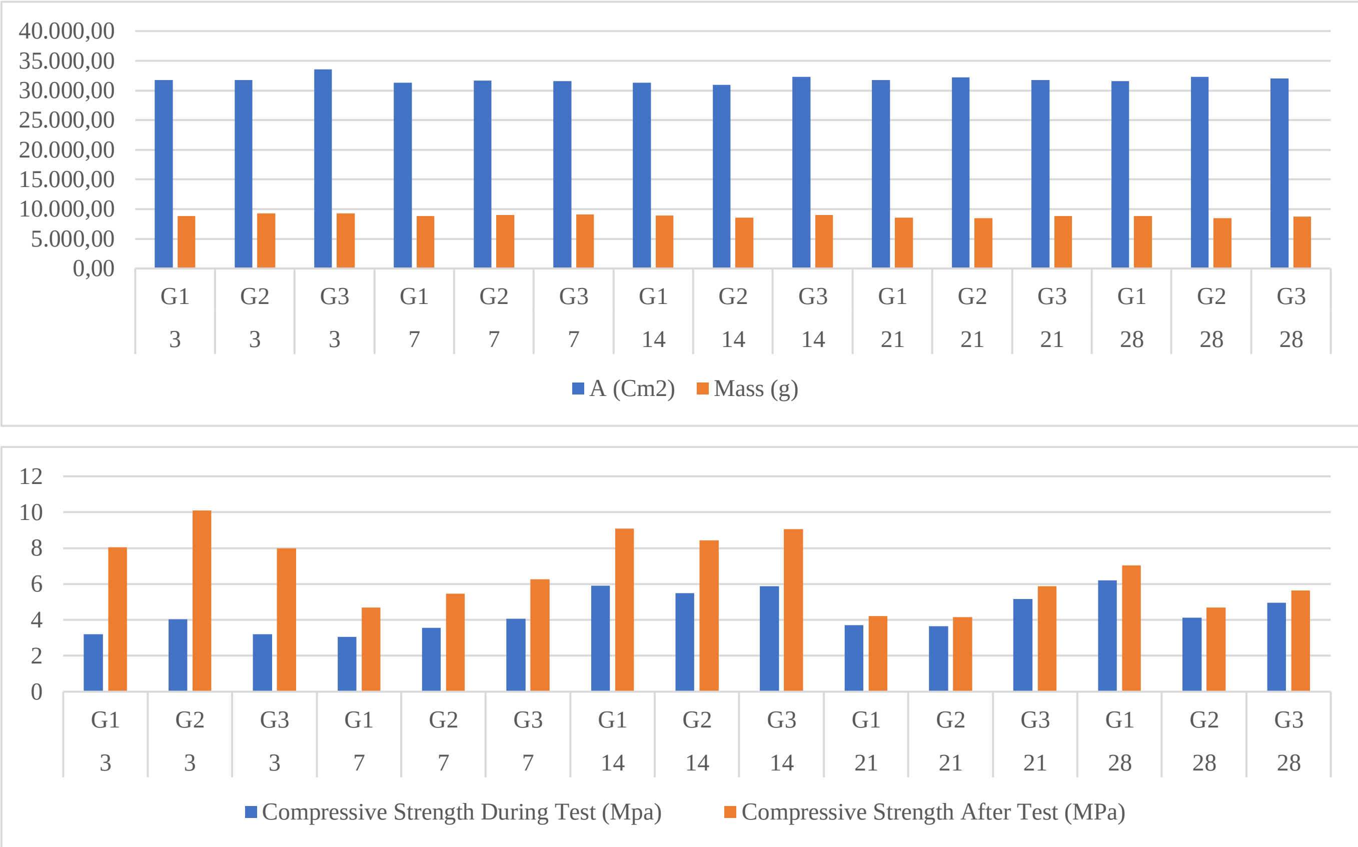

Figure 3. *Upper:* the cross-sectional area of each hollow block in the test object (cm^2) and mass weight in grams; *Bottom:* the compressive strength test results corresponding to each test object, during and after the drying period.

As an additive in concrete, FABA functions as a filler, increasing internal cohesion and reducing the porosity of the transition area which is the smallest area in concrete, making it stronger. Additionally, FABA affects the strength evident in concrete both at the initial drying period of 7 days and 28 days. The increase in concrete compressive strength is caused by a combination of cement hydration and the pozzolanic reaction [4].

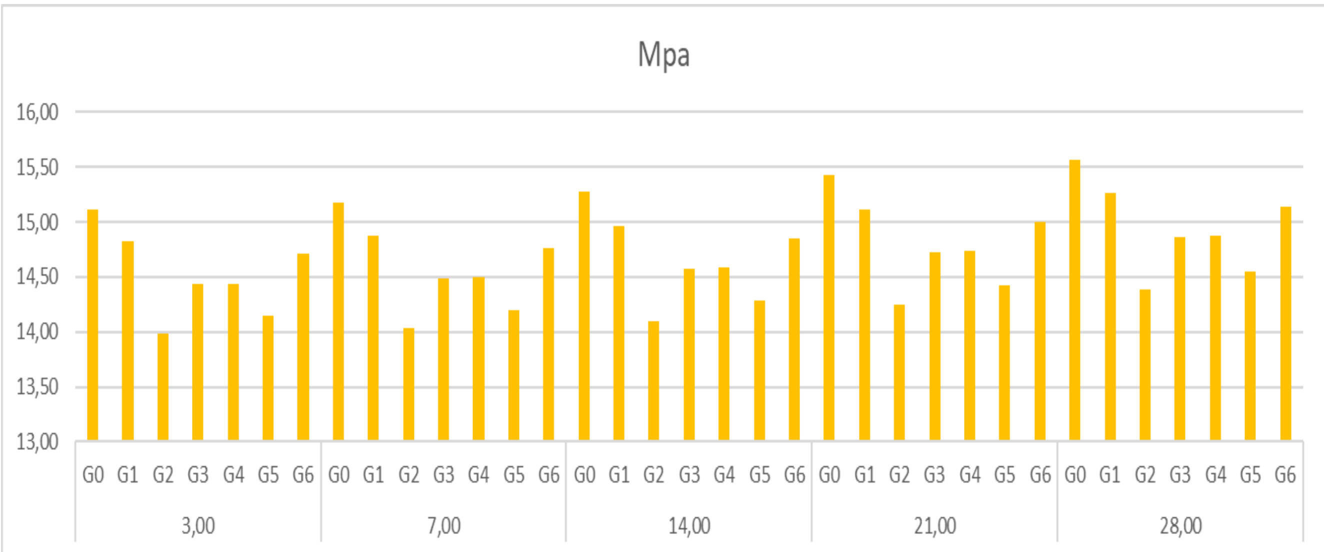

Figure 4. Relationship between compressive strength and material composition of hollow block

3.2.2. The Relationship between Compressive Strength and Material Composition of a Hollow Block Product

Figure 4 shows that the partial replacement of cement with FABA reduces the compressive strength of hollow block products. However, the addition of the mixed volume of FABA increases the compressive strength of the hollow block product.

The lowest compressive strength at 28 days (see Figure 5) is 14.39 MPa, found in G2 with a composition of 0.25 BA. The compressive strength of the hollow block product after the same drying period is 15.56 MPa, without BA replacement (G0, Control). The average compressive strength is 14.95 MPa. Compared to the control group, G1, and G2, experienced a reduction in compressive strength, which started going up from G3 to G6 but not too significantly. Consequently, the replacement of FABA volume, equivalent to 1.25% of the total cement, can increase the compressive strength of hollow block products. Optimum compressive strength was achieved at G6 (FABA composition = 1,25).

According to Tang (2016), FABA in cement mixtures can increase the compressive strength of hollow blocks. SiO_2 in coal ash reacts with the residual lime, which is released during the reaction between cement compounds and water. This reaction produces CaOSiO2 or calcium silicate hydrate (C-S-H) compounds with complex and low solubility properties.

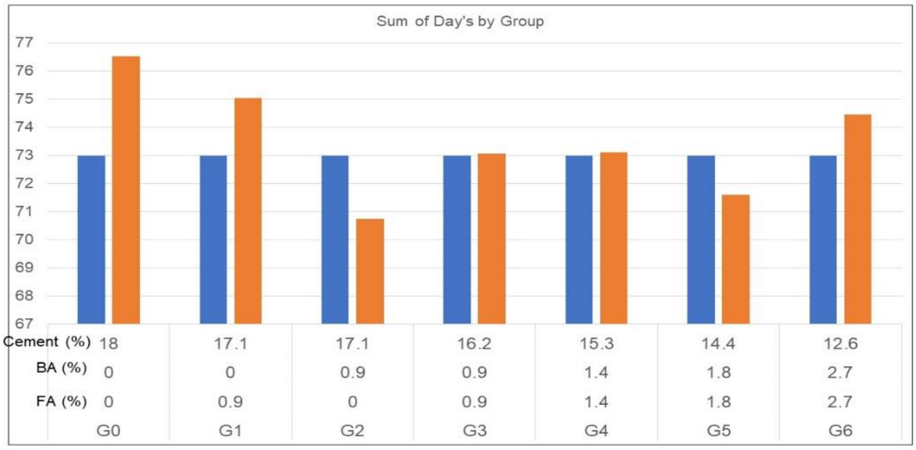

Figure 5. Relationship between compressive strength and material composition of hollow block

The use of FABA as an additive trigger a binding reaction that involves free lime produced during cement hydration. This reaction can be accelerated by the silica in FABA. The smaller size of coal ash grains leads to a greater concrete density because these smaller grains can fill the voids between the aggregate grains, minimizing pores and using the pozzolanic properties of FABA to improve the quality of hollow block products. FABA best serves as an added active ingredient when mixed with lime or cement. Hollow block combined with FABA has higher compressive strength than standard concrete, particularly in specific compositions. FABA can serve as fine aggregate and pozzolan on hollow blocks. It also ensures hollow blocks get higher strength than their ordinary counterparts [13].

3.2.3 ANOVA Test

The results of the one-way ANOVA test provide a significant value of 0.000 (<0.05), indicating that there is a difference in the relationship between compressive strength and the composition of hollow block product material. These modifications are caused by slight changes in the open-block products, which are not too significant. The one-way ANOVA analysis is employed to recognize the mean variations among groups in an experiment that provides more than two distinct samples.

The results of the LSD Post Hoc test on the relationship between compressive strength and material composition of hollow blocks show a significant difference within the experimental group. However, several experimental groups do not show any disparities. When exploring the relationship between K1 and K6, the significant value obtained was 0.302, which is more than the threshold value of 0.05. The significant value in the experiment between K2 and K5 was 0.135 surpassing the threshold of 0.05. Additionally, the experiment between K3 and K4 yielded a significant value of 0.928, which is greater than the threshold of 0.05.

3.3. Cost Analysis

Based on the unit price of building materials in

Indonesia in 2022.

Table 2. Hollow block production cost

For 300 Hollow Block Production		Cost Analysis of FABA Waste Disposal to PPLI		
Cement (50 Kg)	IDR 70.000	FABA Volumes (Kg/day)	1.600	Kg/day
Sand, 1 m3 (1400 Kg)	IDR 235.000	FABA Processing Fee	IDR 26.350.000	/ton
Total Production	IDR 300	Total Cost/day	IDR 42.160.000	/day
Hollow Block Price	IDR 3500			
Price for 300 pieces	IDR 1.050.000			

The cost analysis results demonstrate that the processing of FABA waste complies with government regulations (PPLI), with the companies involved paying a fee of Rp. 42,160,000 per day. By substituting FABA for cement, the expenditure on processing FABA waste can effectively lower the production cost of a hollow block. To achieve this substitution, companies need to incorporate FABA into the mixture of the hollow block product.

Table 2. Analysis of hollow block sales and production costs

Group Test	Production cost (IDR)	Profit (IDR)	Profit per piece (IDR)
G0	691.200,00	358.800,00	1.196,00
G1	673.800,00	376.200,00	1.254,00
G2	673.800,00	376.200,00	1.254,00
G3	621.300,00	428.700,00	1.429,00
G4	586.200,00	463.800,00	1.546,00
G5	551.400,00	498.600,00	1.662,00
G6	516.300,00	533.700,00	1.779,00

Using FABA coal to make a hollow block product benefits the company in many ways. By incorporating FABA coal into the hollow block production process while adhering to the composition of a certain experimental group, the company can achieve higher profits. Moreover, increased FABA coal measurements allow the company to create a hollow block product with various benefits compared to one without additional FABA (see Figure 5).

In connection with efforts to minimize production costs by replacing the amount of cement with FABA, manufacturing hollow blocks is the most suitable and profitable choice in the circular economy of coal FABA.

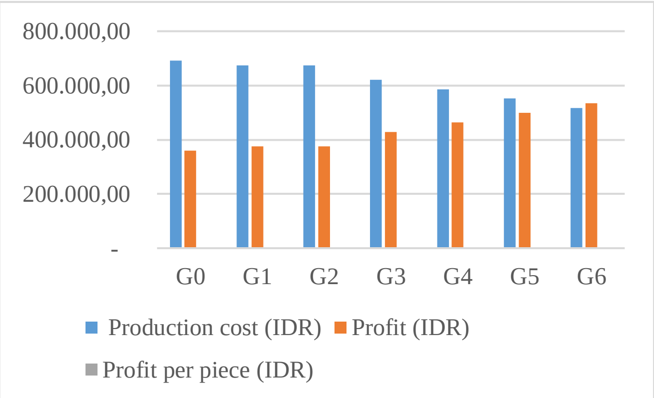

Figure 6. Analysis of hollow block sales and production cost

4. Conclusion

In conclusion, the compressive strength test results based on the material composition of the hollow block product showed significant disparities as follows:

1. Several experimental groups show no significant difference, namely Group 1 and Group 6 with a significance of 0.302 > 0.05; Group 2 with Group 5 with a value of 0.135 > 0.05 and Group 3 with Group 4 with a value of 0.928 > 0.05.
2. Utilization of FABA Coal, it can be concluded that the greater the composition of FABA used in each experimental group, can minimize the value of hollow block production.
3. The greater the FABA mixture used as a substitute for cement in Hollow Block production, the higher the compressive strength value produced with a maximum drying age (28 days)
4. The results of circular economic analysis, the use of FABA in Hollow Block production will provide maximum benefits compared to hollow blocks without FABA mixture. The maximum profit is achieved in Group 6 with a yield per hollow block of IDR 1,779.

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