

Analysis of Economic Feasibility and Compressive Strength of Concrete Based on the Utilization of Red Mud Waste and Sustainable Construction Management

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Keywords

Red Mud; Compressive Strength; Economic Feasibility; Cement Substitution; Net Present Value (NPV); Benefit-Cost Ratio (BCR); Internal Rate of Return (IRR); Life Cycle Assessment (LCA); Life Cycle Inventory (LCI); Life Cycle Impact Assessment (LCIA); Interpretation

ABSTRACT

This research examines red mud as a partial cement substitute in concrete, comparing normal concrete with 25% red-mud concrete (RM25) based on compressive strength, economic feasibility, waste absorption, and LCA environmental impact. Compressive strength tests were conducted at KAN-accredited Wika Beton Laboratory, and economic feasibility was evaluated using NPV, BCR, and IRR for paving-block production. The waste absorption capacity was calculated based on an annual production volume of 5,000 m². The LCA assessment was carried out in accordance with ISO 14040:2006, covering goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation. The results showed that RM25 achieved a compressive strength of 36.93 MPa at 30 days, higher than normal concrete with 34.15 MPa. Economically, RM25 recorded a production cost of IDR 1,480,085/m³, with a positive NPV, an IRR of 43.9%, and BCR > 1. In addition, RM25 enabled the absorption of approximately 41.8 tons of red mud waste per year in paving-block production. The LCA results also indicated a reduction in environmental impacts, particularly in the global warming potential category, due to reduced cement consumption. Overall, the 25% red-mud formulation is considered feasible for practical implementation as it meets both technical and economic requirements while providing environmental benefits through emission reduction and enhanced industrial waste utilization.

INTRODUCTION

Indonesia has large bauxite reserves and is the world's sixth-largest bauxite ore producer in 2019 with a production of 370 million tons and a total reserve of around 1.2 billion tons (4% of world reserves) (Johansen, 2023; Lezziero, 2023). The bauxite processing industry in West Kalimantan produces Smelter Grade Alumina and Chemical Grade Alumina with red mud waste of around 1.25 million tons per year. Red mud is highly alkaline (pH 11.5–13), red, smooth, and contains Fe₂O₃, TiO₂, and SiO₂. As global sustainability demands increase, the implementation of Sustainable Construction Management (SCM) is important to close the construction material cycle and maximize waste utilization.

Previous research has examined the use of red mud in construction materials (Gheisari et al., 2023; Wei et al., 2023). Investigated the potential of red mud as a cement replacement and found that it could improve certain properties of concrete. Sawant et al. (2016) studied partial replacement of cement with red mud in concrete and reported acceptable compressive strength at lower substitution levels. Rathan et al. (2013) conducted experimental studies on red mud concrete and noted its feasibility for non-structural applications. Mohammed et al. (2021)

analyzed the effect of partial cement replacement using bauxite residue and confirmed technical viability. Pavan et al. (2016) examined cement and sand replacement with red mud and quarry dust in pavement concrete. Wang et al. (2018) reviewed reutilization of red mud in cement production, identifying mechanisms, challenges, and prospects. Humphrey et al. (2019) studied replacing sand with bauxite mining waste in concrete production in Ghana. Vian et al. (2023) conducted economic analysis and compressive strength evaluation of solid waste utilization in concrete.

However, there is a research gap in the use of red mud as a construction material in Indonesia (Abdul et al., 2025; Al - Fakhri et al., 2023; Hakim et al., 2023; Meilasari et al., 2024; Singh et al., 2024; Svobodova-Sedlackova et al., 2024). Previous research has focused more on fly ash and slag, and dominated to evaluate technical aspects, while economic and environmental feasibility studies are still limited (Hossain et al., 2026; Joseph et al., 2026; Mohammed et al., 2025; Vilakazi et al., 2022). Therefore, this study fills this gap by assessing the technical, economic, and environmental feasibility of using red mud in concrete through a cost-benefit approach and Life Cycle Assessment (LCA) to determine its potential implementation in the construction industry.

This research was formulated to answer the following four main problems (1) Can *red mud* waste be used as an additive in road pavement like the use of concrete? (2) How does the variation in the percentage of red mud substitution (25%) affect the compressive strength of concrete, and does normal concrete show strength advantage over other formulations containing red mud? (3) How much potential for red mud waste absorption can be achieved through the use of red mud concrete in precast pavement production models? (4) Does the use of red mud waste in the production of precast concrete have economic feasibility, as evidenced by economic analysis such as Net Present Value (NPV), Benefit Cost Ratio (BCR), and Internal Rate of Return (IRR)? The novelty of this research lies in the use of *red mud waste* as an additive to concrete in the construction of precast concrete pavement, as well as examining its economic feasibility.

The objectives of this research are to investigate the utilization of red mud waste as a partial cement substitute in concrete, to compare the compressive strength of normal concrete with 25% red-mud concrete (RM25), to evaluate the economic feasibility of red-mud concrete in paving-block production using NPV, BCR, and IRR, to calculate the waste absorption capacity from red mud utilization, and to assess the environmental impact reduction through Life Cycle Assessment (LCA) in accordance with ISO 14040:2006. The benefits of this research are twofold. Theoretically, this study contributes to the literature on sustainable construction materials by providing empirical evidence on the technical, economic, and environmental performance of red-mud concrete, filling the gap in integrated assessments that combine compressive strength, economic feasibility, and LCA. Practically, this research benefits several parties. For the construction industry, the findings offer an alternative sustainable material that reduces cement consumption and production costs. For waste management authorities, this study provides a solution for utilizing bauxite residue (red mud) that accumulates in landfills. For policymakers, the results support the development of regulations promoting industrial waste utilization in construction. For future researchers, this

study serves as a reference for integrated assessment of other industrial waste materials in concrete production.

This study has certain limitations to maintain the focus and validity of the results. The red mud samples used came from the landfill location carried out by PT. Syntegra Techno International in Mempawah, West Kalimantan. The primary technical analysis is focused on testing the compressive strength of concrete on 7, 14, 28, and 30-day old cylindrical test pieces. For the concrete mix design, the target compressive strength (f_c) was set at 25 MPa, with a controlled water-cement factor (W/C) ratio of 0.39, and a plan slump of 12 ± 2 cm, which was confirmed by the actual slump during the test. Meanwhile, the analysis of material and labor costs is based on the Unit Price Analysis (UPA) standard of West Kalimantan Province in 2025, and all concrete compressive strength tests are carried out in the laboratory of PT. WIKA Pratama Learning Centre, Cibubur. This limitation ensures that research findings are relevant to Indonesia's local conditions and context.

RESEARCH METHOD

This research used an experimental approach, where a series of experiments were carried out to prove that red mud waste can be used as an additive for concrete that is suitable for use in construction. The test is carried out both from a technical point of view through a concrete compressive strength test, and from an economic point of view by analyzing the feasibility of using waste as a construction material. This study was conducted to evaluate the technical, economic, and environmental feasibility of using red mud as a partial cement substitution in concrete with a comparative focus on normal concrete and 25% red mud concrete. The research methodology is designed to produce outputs on four main indicators, namely (1) Concrete compressive strength test results, (2) utilization and volume of economic waste absorption, (3) economic feasibility and (4) environmental impact through Life Cycle Assessment (LCA).

This research began with a literature study to obtain information about the specifications and characteristics of red mud, then continued with sampling in the red mud landfill area in Mempawah, West Kalimantan. The samples obtained are then dried and prepared for trial mix needs in the laboratory at the next stage. The design of the concrete mixture was carried out with reference to the mixed design method based on SNI 03-2834-2000 concerning Procedures for Making Normal Concrete Mix Plan, with a target compressive strength of 25 MPa at the age of 28 days and a slump value of 10–12 cm. The materials used consist of type I portland cement, fine aggregate, coarse aggregate, water, and red mud as a partial substitution of cement of 25% of the weight of cement.

The stage of making the test specimen begins with weighing materials in the form of cement, red mud, fine aggregate, coarse aggregate, and water according to the proportions of the mixed design. Furthermore, the material is mixed using a concrete mixer. then slump testing is carried out according to ASTM C143 or SNI 03-1972-1990 to assess the ease of workmanship. The concrete mixture that meets the slump criteria is then poured into 150 mm \times 300 mm cylindrical molds, compacted using vibrators to reduce air cavities, and flattened the top surface and then given an identity code. The test specimen is left for 24 hours before being removed from the mold and then treated by immersion (curing) in a water bath until it reaches the test life. Compressive strength testing was carried out at the age of 7, 14, 28, and 30 days at the Wika Beton Laboratory which has obtained accreditation from the National

Accreditation Committee (KAN). Before the test, the capping process is carried out to ensure an even distribution of tension during loading so that the compressive strength value obtained is more valid.

Table 1 Mix Design Concrete with Red Mud

Formulation	Cement	Red Mud	White Sand	W.M Sand	Coarse Aggregation Max 25 mm	Water	Delay	Super
	Kg/m ³	Kg	Kg	Kg	Kg	Liters	Liters	plasticizer Liters
Normal Concrete	312	0	532.9	299.97	949.9	165	1.25	2.96
Red mud 5%	296.3	15.63	532.9	299.97	949.9	145.44	1.25	2.96
Red mud 15%	265.2	46.72	532.9	299.97	949.9	145.44	1.25	2.96
Red mud 20%	249.6	62.35	532.9	299.97	949.9	136.35	1.25	2.96
Red mud 25%	269.97	89.99	533.03	299.97	949.9	127.26	1.25	4.30
Red mud 30%	251.97	107.98	533.03	299.97	949.9	127.26	1.25	4.30

Source : Data Processing (2025)

The economic feasibility analysis was carried out to predict the viability of the implementation of 25% red mud concrete on an industrial scale. The calculated cost parameters include material costs, production costs, initial investment costs, annual operating costs, and product selling prices. The analysis was carried out using three basic parameters, namely net present value (NPV), *Benefit Cost Ratio* (BCR) and *Internal Rate of Return* (IRR).

The Life Cycle Assessment (LCA) analysis was carried out to assess the potential to reduce environmental impact due to the use of red mud as a substitution material in concrete formulations, with substitution variations of 0% (baseline), 5%, 15%, 20%, 25%, and 30%. The analysis was carried out using SimaPro software because it supports the ISO 14040:2006 standard which includes the stages of Goal and Scope Definition, Life Cycle Inventory, Life Cycle Impact Assessment, and Interpretation. In this study, the functional unit used is the production of 1 cubic meter (1 m³) of ready-to-use concrete with a cradle-to-gate system limit, which includes the process from raw material extraction to concrete production process.

At the inventory life cycle stage, analysis is carried out on two main processes, namely the delivery of raw materials (raw material transportation) and the concrete mixing process. The impact assessment method used is Eco-indicator 99 (E) from Europe, which displays eleven impact categories. For the red mud transportation process, a pick-up type vehicle with a carrying capacity of 1,200 kg is used from the landfill location to the PT Syntegra Techno International workshop 18 km away, with a diesel fuel consumption of 12 km/liter (assuming Mitsubishi L300). Delivery is carried out according to the percentage of red mud use in each substitution formulation.

RESULT AND DISCUSSION

Normal Concrete Formulation

In this study, normal concrete was used as a control formulation to be compared with concrete that was substituted with red mud by 25%. Normal concrete is used as a reference in the evaluation of compressive strength and cost analysis per cubic meter. The composition of a normal concrete mix design consists of: (1) cement 312 kg, (2) white sand 533 kg, (3) W.M sand 300 kg, (4) coarse aggregate 950 kg, (5) water 165 kg, (6) retarder 1.25 L, and (7) superplasticizer 2.06 L with an actual slump of 10 ± 2 cm. The results of the compressive strength test up to 30 days of life showed that normal concrete reached a maximum compressive strength of about 34.2 MPa or $\pm 137\%$ of the planned compressive strength ($F_c'25$). Based on the unit cost analysis, normal concrete has a production cost of IDR 1,523,108 per m^3 .

Table 2 Normal Concrete Compressive Strength Test Results

UJI KUAT TEKAN BETON SILINDER													
WIKALAB & DIGITAL SOLUTION													
LABORATORIUM JASA KONSTRUKSI													
PT WIKALAB KARYA (Persero) Tbk Jl. Raya Selatan Dua Utama no. 8 Cikarang - Bekasi Timur 17512 Telp. 08 57100001 Fax. 08 57100002 Email: info@wikalab.com													
No. SPTS: 0013													
Pemohon : Muhamad Reza Maulana													
Proyek : Tesis Universitas Mercu Buana (Analisis Kelayakan Kuat Tekan Beton Berbasis Pemantauan Limbah Red Mud 0%)													
Kontraktor :													
Suhu Ruangan : 31 °C Kelembaban : 58%													
No. Laporan : WIKALAB / 102.BT/IX/2025													
Tanggal : 08 September 2025													
Mutu Beton : f'c 25													
Slump Rencana :													
No	Date		Age	Specimen	Grade	Size of	Weight	Unit Weight	Load	Strength	Strength in Mpa		
	Casting	Testing	(days)	code		Cylinder	(gram)	(gr/cm ³)	(kN)	(Kg/Cm ²)	(Kg/Cm ²)	%	
1	9-Aug-25	16-Aug-25	7	Fc 25 Mpa Normal	FC 25	Ø 15 x 30	12.636	2,39	457,2	263,8	25,9	104%	
2	9-Aug-25	23-Aug-25	14	Fc 25 Mpa Normal	FC 25	Ø 15 x 30	12.668	2,39	536,5	309,6	30,4	122%	
3	9-Aug-25	06-Sep-25	28	Fc 25 Mpa Normal	FC 25	Ø 15 x 30	12.710	2,40	626,5	361,5	35,5	142%	
4	9-Aug-25	08-Sep-25	30	Fc 25 Mpa Normal	FC 25	Ø 15 x 30	12.732	2,403	603,2	348,1	34,2	137%	

Source : Concrete Wika Test Results (2025)

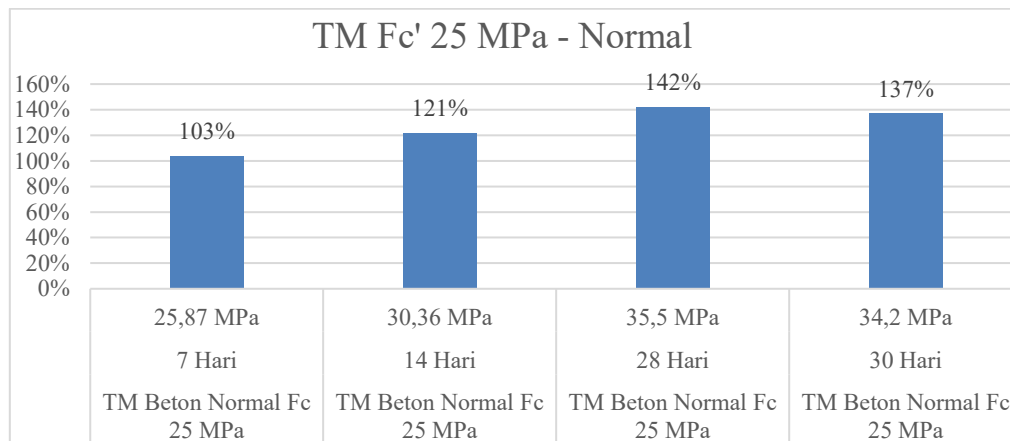


Figure 1 Normal Concrete Compressive Strength Graph

Source: Author's analysis based on concrete compressive strength test results at Wika Beton Laboratory, 2025

Red Mud Concrete Formulation 25%

Concrete formulation with 25% red mud substitution was carried out by adjusting the material composition with the following details: (1) cement 269.97 kg, (2) red mud 89.99 kg, (3) white sand 533.03 kg, (4) W.M sand 299.97 kg, (5) coarse aggregate 949.90 kg, (6) water

127.26 L, (7) retarder 1.25 L, and (8) superplasticizer 4.30 L, with an actual slump of 12.2 cm. The results of the compressive strength test showed that concrete with 25% red mud still met the compressive strength of the design with technical performance that can be directly compared to normal concrete. From the total unit cost analysis, 25% red mud concrete has a production cost of Rp 1,480,085 per m³, showing economic efficiency compared to normal concrete without substitution.

Table 3 Concrete Compressive Strength Test Results with Red Mud 25%

No	Date		Age (days)	Specimen code	Grade	Size of Cylinder	Weight (gram)	Unit Weight (gr/cm ³)	Load (KN)	Strength (kg/cm ²)	Strength in Mpa (kg/cm ²)	%
	Casting	Testing										
1	18-Dec-25	20-Dec-25	7	Fc 25 Mpa + Red Mud 25%	FC 25	Ø 15 X 30	12.316	2,36	531,7	306,8	30,1	120%
2	18-Dec-25	27-Dec-25	14	Fc 25 Mpa + Red Mud 25%	FC 25	Ø 15 X 30	12.800	2,38	484,0	279,5	27,4	110%
3	18-Dec-25	30-Jan-26	28	Fc 25 Mpa + Red Mud 25%	FC 25	Ø 15 X 30	12.872	2,45	623,3	359,7	35,3	141%
4	18-Dec-25	12-Jan-26	30	Fc 25 Mpa + Red Mud 25%	FC 25	Ø 15 X 30	12.768	2,41	652,1	376,6	36,9	148%

Source : Concrete Wika Test Results (2025)

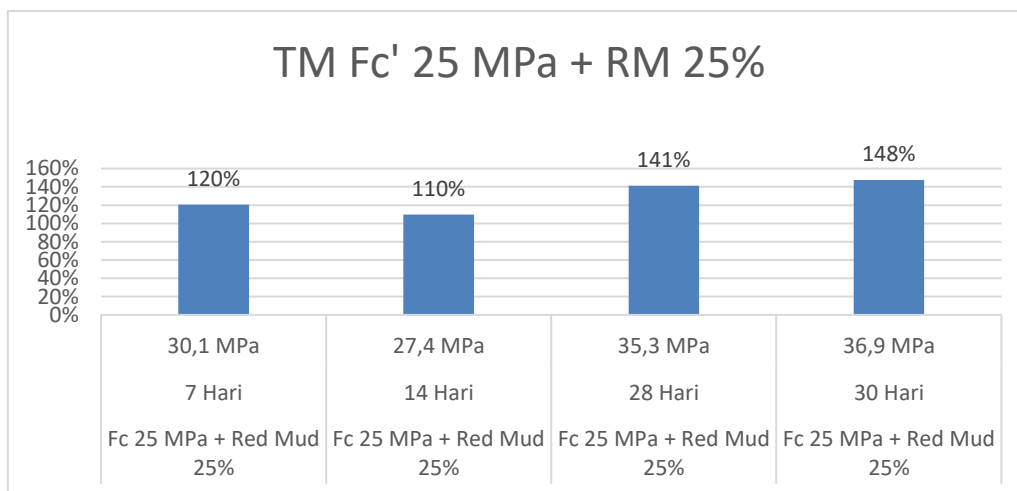


Figure 2 Red Mud Concrete Compressive Strength Graph 25%

Source: Author's analysis based on concrete compressive strength test results at Wika Beton Laboratory, 2025

Red Mud Utilization Model

The use of red mud waste has the potential for various civil engineering applications, such as paving blocks, bricks, canteens, fence panels, and coastal protective concrete. In this study, red mud is focused as a partial cement substitution material in the production of precast paving blocks. Paving blocks themselves are pavement elements that are arranged in a certain pattern and lock each other so that they form a strong, stable, and easy surface to install or replace. This product is widely used in road infrastructure and parking areas because the production process is fast and its installation is practical in the field.

In addition to being a solution in industrial waste management, the use of red mud in precast products also has economic value because the production process can be carried out en masse using repeated molds and has wide market potential. For example, when red mud-based

paving blocks are applied to a residential area of 5,000 m², the material not only meets the needs of construction but also directly reduces the volume of bauxite residues deposited in landfills and turns them into value-added products. This approach supports the principles of Sustainable Construction Management because it utilizes waste, improves material efficiency, and opens up new economic opportunities for the construction sector.

For analysis purposes, this study used brick-type paving blocks measuring 10.5 × 21 × 8 cm. With these dimensions, 1 m³ of concrete mixture produces about 12.5 m² of paving blocks. Based on the Analysis of Work Unit Prices (AHSP) of West Kalimantan Province, the basic price of 8 cm thick K-300 quality brick paving blocks is Rp 167,200 per m² or around Rp 3,800 per piece (44 pieces per m²). Thus, the economic value of paving blocks can be calculated in cubic units based on the production volume produced from 1 m³ of concrete mixture. In the substitution of red mud of 20%, the production volume remains the same, namely 12.5 m² of paving blocks per 1 m³, so that the comparison of the economic value can be analyzed with normal concrete and conventional paving blocks in units of volume and area.

Table 4 Price Comparison of Paving blocks/m²

Concrete Type	Concrete Price (Rp/ m ³)	Paving Yield (m ³ / m ²)	Paving Price (Rp/m ²)	Difference (Save) / m ²
Normal Concrete	IDR 1,523,108	12.5	IDR 167,200	-
Red mud 5%	IDR 1,495,249	12.5	IDR 119,619	IDR 47,581
Red mud 15%	IDR 1,435,729	12.5	IDR 114,858	IDR 52,342
Red mud 20%	IDR 1,404,794	12.5	IDR 112,383	IDR 54,817
Red mud 25%	IDR 1,480,085	12.5	IDR 118,406	IDR 48,794
Red mud 30%	IDR 1,445,240	12.5	IDR 115,619	IDR 51,581

Source : Data Processing (2025)

Potential Waste Volume Reduction

The following are the results of the calculation of the potential absorption of red mud waste in the production of paving blocks on a large scale. Calculations were made for the need for concrete volume in the production of paving blocks covering an area of 5,000 m² with variations of red mud mixture of 5%, 15%, and 20% of the total cement weight. This analysis results in an estimate of the volume of red mud absorbed per cubic meter of concrete as well as its total utilization in one year of production. In general, the higher the percentage of red mud in the mixture, the greater the amount of waste that can be utilized.

Table 5 Calculation of Waste Absorption Potential in Red Mud Utilization

Formulation	Mixing in paving production 5000 m ² (m ³ / m ²)	Red mud Waste Volume /m ³ in Paving Production (Kg)	Potential Waste Absorbed Year	Potential Waste Absorbed (Tons)
Normal	465.1	0	0	0
Red mud 5%	465.1	15,63	7.269 kg	7.2 Tons
Red mud 15%	465.1	46,72	21.729 kg	21.7 Tons

<i>Red mud</i> 20%	465.1	62,35	28.998 Kg	28.9 Tons
<i>Red mud</i> 25%	465.1	89,99	41.854 kg	41.8 Tons
<i>Red mud</i> 30%	465.1	107,98	50.221 kg	50.2 Tons

Source : Data Processing (2025)

Economic Feasibility Analysis

After identifying the market potential and production volume, the next stage is to analyze the economic feasibility aspects of the project. This analysis determines whether the investment in the treatment of red mud waste into construction products (such as paving blocks) provides adequate added value and is feasible. To calculate Net Present Value (NPV), an **Initial Investment (Initial Investment I_0)** of IDR 300,000,000 is required which is used, among other things, for purchases.

Table 6 Details of the Initial Investment Fee

Cost Component	Units	Quantity	Unit Price (Rp)	Total Price (Rp)
Hydraulic Paving Press Machine	2	Units	IDR 42.500.000,00	IDR 85,000,000
Concrete mixer capacity 300 L	2	Units	IDR 9,000,000,00	IDR 18,000,000
Paving mold	5	Shape	IDR 2,000,000.00	IDR 10,000,000
Scales & aids	1	Ls	IDR 2,000,000.00	IDR 2,000,000
Working capital (1 month material stock)	1	Ls	IDR 65,000,000,00	IDR 65,000,000
Production warehouse 6mx12m	1	Ls	IDR 100,000,000,00	IDR 100,000,000
Electricity and water	1	Ls	IDR 10,000,000,00	IDR 10,000,000
HR licensing and training	1	Ls	IDR 10,000,000,00	IDR 10,000,000
Total Initial Investment I_0 Block Paving Production Cost				IDR 300,000,000

Source : Data Processing (2025)

As well as annual operational costs (Ct) of IDR 640,000,000 per year, which are allocated for various operational needs such as additional raw materials, energy, labor, equipment maintenance, and other production support costs, including:

Table 7 Annual Operating Fee Details

Cost Component	Units	Quantity	Unit Price (Rp)	Total Price (Rp)
Workforce	12	Moon	IDR 15,000,000	IDR 180,000,000
Electricity and water	12	Moon	IDR 950,000	IDR 11,400,000
Main raw materials	12	Moon	IDR 34,000,000	IDR 408,000,000
Transport & distribution	12	Moon	IDR 2,000,000	IDR 24,000,000
Equipment maintenance & warehouse	1	Ls	IDR 7,000,000	IDR 7,000,000
Administration & Promotion	12	Moon	IDR 800,000	IDR 9,600,000
Total Annual Operating Expenses (Ct)				IDR 640,000,000

Source : Data Processing (2025)

a. Net Present Value (NPV)

Net Present Value (NPV) is an investment analysis method used to measure the present value of all net *cash flows* that are expected to be received in the future, then the value is subtracted by the initial investment value (I_0). NPV represents the difference between the discounted cash in *value* and the cash out value (including the initial investment), all of which are measured at the current time value of money (period zero).

Eligibility Criteria:

- If the NPV > 0: The project is feasible to implement, because the project generates returns that exceed the required discount rate.
- If NPV < 0: The project is not *feasible* to implement.
- If NPV = 0: The project is on breakeven.

$$NPV = \sum_{\{t=0\}}^n \frac{B_t - C_t}{(1+i)^t} \quad NPV = \sum_{\{t=1\}}^n \frac{NCF_t}{(1+i)^t} - I_0$$

Note:

NCF_t : *Net Cash Flow / Benefit-cost* in the year t

I_0 : *Initial Investment*

i : *Discount rate/Interest rate (%)*

t : 0,1,2,3rd year,..... to $-n$

n : *Project age year*

B_t : *Revenue obtained in the year $-t$ (Rp)*

C_t : *Expenses incurred in the t th year (Rp)*

From the initial investment of Rp 300 million the project produces a Net Cash Flow (NCF) of Rp 196 million per year for ten years, from the difference between the annual Benefit and Cost. After all these future cash flows are discounted back to the Present Value with a discount rate of 8%, the total Present Value generated is IDR 1,015,175,954. Thus, the total Present Value Net Cash Flow minus the Initial Investment produces a positive Net Present Value (NPV) of IDR 715,175,954.

The Net Present Value (NPV) calculation using a discount rate of 8%, which consists of a base interest rate of 5.5% and a risk premium of 2.5%. The project requires an initial investment of IDR 300,000,000 in year zero and generates a constant annual net cash flow of IDR 196,000,000 from 2026 to 2035, derived from annual benefits of IDR 836,000,000 and costs of IDR 640,000,000. After discounting the net cash flows over the 10-year analysis period, the total present value of net cash flows amounts to IDR 1,015,175,954, resulting in a positive NPV of IDR 715,175,954, which indicates that the project is financially feasible.

b. Benefit-Cost Ratio (BCR)

The *Benefit Cost Ratio* (BCR) method is one of the main instruments in financial feasibility studies used to evaluate the economic efficiency of a project. BCR is defined as the ratio between the present *value* of the total benefit *that the project will get to the present value* of the total cost incurred during the economic life of the project.

The main purpose of BCR calculation is to measure the financial benefits that can be generated by each unit of cost invested, after taking into account the *Time Value of Money*

$$BCR = \frac{\sum_{t=0}^T \frac{B_t}{(1+r)^t}}{\sum_{t=0}^T \frac{C_t}{(1+r)^t}}$$

through the *discounting process*.

This project resulted in a Total Present Value Benefit of IDR 5,609,628,050 and a Total Present Value Cost of IDR 4,294,452,095 over a period of 10 years, discounted at a rate of 8%. Therefore, from the comparison of the two Present Value values, a Benefit-Cost Ratio (BCR) of 1.31 was obtained (feasible, having a value greater than 1).

the Benefit–Cost Ratio (BCR) analysis using a discount rate of 8%, which combines a base interest rate of 5.5% and a risk premium of 2.5%. Over the period from 2026 to 2035, the project generates annual benefits of IDR 836,000,000 and annual costs of IDR 640,000,000, which are discounted to obtain their present values. The total present value of benefits amounts to IDR 5,609,628,050, while the total present value of costs is IDR 4,294,452,095. The resulting BCR of 1.31, which is greater than one, indicates that the project is economically feasible, as the present value of benefits exceeds the present value of costs.

In the analysis of this *red mud* processing project, the evaluation is carried out for a period of 10 years with a discount rate set at 8% per year.

c. Internal Rate of Return (IRR)

The *internal Rate of Return* (IRR) is a discount *rate* that equals the present value of total cash inflows with the present value of total cash outflows (including initial investments). In other words, IRR is a discounted rate that results in a Net Present Value (NPV) equal to zero (NPV = 0).

The *Internal Rate of Return* (IRR) method is used to determine the internal rate of return of an investment, which is the interest rate that makes the NPV value equal to zero. IRR reflects the ability of a project to generate a return relative to the magnitude of the investment.

$$IRR = i_1 + \frac{NPV_1}{NPV_1 + NPV_2} (i_2 - i_1)$$

Note:

NCF : Net Cash Flow (Benefit + Depreciation – Cost)

*I*₀ : Initial Investment

*i*₁ : 8% Discount rate = 5.5% BI rate + 2.5% project risk."

*i*₂: 20% Test limits commonly used in economic feasibility analysis

MARR: *Minimum Attractive Rate of Return* (MARR)

Analysis (IRR) is used to find the discount rate that makes the project's Net Present Value equal to zero. Based on the calculations below, the internal rate of return of this project is very high, which is 63.9%. This value exceeds the company's Minimum Attractive Rate of Return (MARR) set by 20%.

$$IRR = i_1 + \frac{NPV_1}{NPV_1 + NPV_2}(i_2 - i_1) \quad IRR = 8\% + \frac{1.915.555.556}{1.915.555.556 + 1.660.000}(20\% - 8\%)$$

$$IRR = 63.9\%$$

Table 10 Calculation of Internal Rate of Return (IRR)

Year	Cost (C.)	Cash in		Depreciation/ Aset 12.5%	Net Cash Flow (NFC) Benefit + Depreciation - Cost	Discounted Cash Flow (DCF) <i>i</i> 2- <i>i</i> 1	
		Benefit (B.)				NPV 1 (8%)	NPV 1 (20%)
2025	Rp 640.000.000					-Rp 640.000.000	-Rp 640.000.000
2026	Rp 640.000.000	Rp 836.000.000	Rp 80.000.000	Rp 80.000.000	Rp 276.000.000	Rp 255.555.556	Rp 230.000.000
2027	Rp 640.000.000	Rp 836.000.000	Rp 80.000.000	Rp 80.000.000	Rp 276.000.000	Rp 255.555.556	Rp 230.000.000
2028	Rp 640.000.000	Rp 836.000.000	Rp 80.000.000	Rp 80.000.000	Rp 276.000.000	Rp 255.555.556	Rp 230.000.000
2029	Rp 640.000.000	Rp 836.000.000	Rp 80.000.000	Rp 80.000.000	Rp 276.000.000	Rp 255.555.556	Rp 230.000.000
2030	Rp 640.000.000	Rp 836.000.000	Rp 80.000.000	Rp 80.000.000	Rp 276.000.000	Rp 255.555.556	Rp 230.000.000
2031	Rp 640.000.000	Rp 836.000.000	Rp 80.000.000	Rp 80.000.000	Rp 276.000.000	Rp 255.555.556	Rp 230.000.000
2032	Rp 640.000.000	Rp 836.000.000	Rp 80.000.000	Rp 80.000.000	Rp 276.000.000	Rp 255.555.556	Rp 230.000.000
2033	Rp 640.000.000	Rp 836.000.000	Rp 80.000.000	Rp 80.000.000	Rp 276.000.000	Rp 255.555.556	Rp 230.000.000
2034	Rp 640.000.000	Rp 836.000.000	Rp 80.000.000	Rp 80.000.000	Rp 276.000.000	Rp 255.555.556	Rp 230.000.000
2035	Rp 640.000.000	Rp 836.000.000	Rp 80.000.000	Rp 80.000.000	Rp 276.000.000	Rp 255.555.556	Rp 230.000.000
Total NPV1 & NPV2						Rp 1.915.555.556	Rp 1.660.000.000
						Rp 1.915.555.556	
IRR							63,9%
Minimum Attractive Rate of Return (MARR)							20%
IRR > MARR							43,9%

Source : Data Processing (2025)

Life Cycle Assessment (LCA)

The Life Cycle Assessment (LCA) analysis was used to evaluate the potential environmental impact reduction of the use of red mud as a substitute material in concrete formulation. The substitution variations analyzed included 0% (baseline), 5%, 15%, 20%, 25%, and 30%. The calculation process is carried out using SimaPro software which supports the ISO 14040:2006 standard, which includes the Goal and Scope Definition, Life Cycle Inventory, Life Cycle Impact Assessment, and Interpretation stages. In this study, the functional unit used is the production of concrete as much as 1 m³ with the limit of the cradle-to-gate system, which starts from the extraction of raw materials to the concrete production process.

The inventory stage includes two main processes, namely the delivery of raw materials and the concrete mixing process. The environmental impact assessment was carried out using the Eco-indicator 99 (E) Europe method which featured eleven impact categories. For red mud transportation, a pick-up type vehicle with a carrying capacity of 1,200 kg is used from the landfill to the PT Syntegra Techno International workshop with a distance of 18 km and diesel fuel consumption of 12 km/liter (assuming Mitsubishi L300). The volume of delivery is adjusted to the proportion of red mud use in each substitution variation.

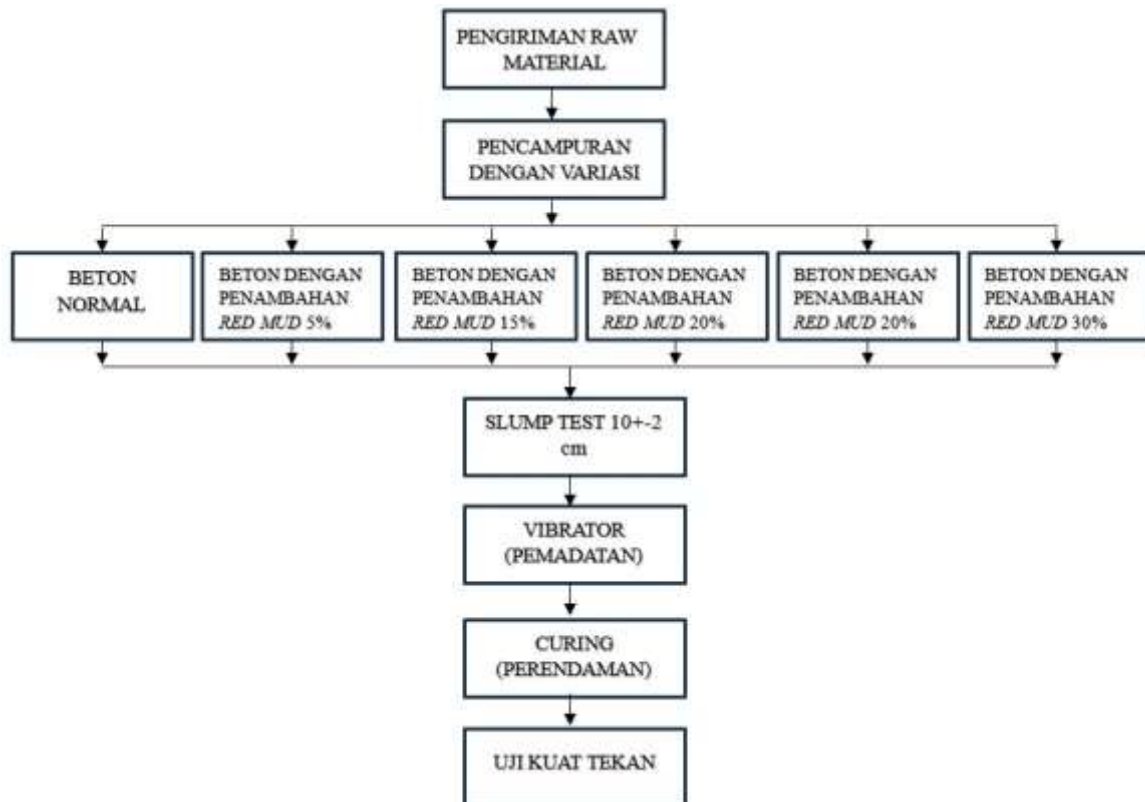


Figure 3 Hierarchical Structure of poses in SimaPro

Source: Author's documentation from SimaPro software analysis, 2025

Table 11 Composition of Normal and Red Mud Concrete Materials 25% per 1 m3

Formulation	Cement	Red Mud	White Sand	W.M Sand	Coarse Aggregation Max 25 mm	Water	Delay	Super plasticizer	Total Weight
	Kg/m3	Kg	Kg	Kg	Kg	Liters	Liters	Liters	Kg
Normal Concrete F'c 25	312	0	532,9	299,97	949,9	165	1,25	2,96	2263,98
Red mud 25%	269,97	89,99	533,03	299,97	949,9	127,2 6	1,25	4,3	2275,67

Source : Data Processing (2025)

a. Life Cycle Inventory

1. Life Cycle Inventory Normal Concrete

In the production of precast concrete, the author conducts two life cycle analyses (*Life Cycle Analysis*), namely at the stage of delivering raw materials and at the *mixing* stage of concrete.

a) Shipping RAW Material

Delivery of raw materials and mixing/*mixing* of concrete Carrying capacity using Pick Up with a carrying capacity of 1200 Kg, assuming that it is sent from the *Mempawah* landfill *location* to the workshop of PT. Syntegra Techno International with a distance of 18 Km, Diesel Requirement of 12 km/Liter (Mitsubishi L300 Assumption). Shipping is divided per percentage of *red mud usage*.

Normal Concrete / Red *mud* use 0%

- Pick up carrying capacity

$$= \text{Carrying Capacity} \times \text{Distance Traveled}$$

$$= 1,2 \text{ ton} \times 18$$

$$= 21,6 \text{ tkm}$$
- Raw material conveying capacity

$$= \frac{\text{Amount of Raw Materials}}{\text{Carrying Capacity}} \times \text{Pick up carrying capacity}$$

$$= \frac{2263,98}{1200} \times 21.6 \text{ tkm}$$

$$= \frac{2263,98}{1200} \times 21.6$$

$$= 40,752$$
- Diesel Consumption

$$= \text{Fuel (Diesel) Requirement} \times \text{Travel Distance}$$

$$= 1/12 \times 18$$

$$= 1,5 \text{ Liter}$$

Table 12 Life Cycle Inventory (LCI) Normal Concrete

NORMAL CONCRETE					
INPUT			OUTPUT		
MATERIAL	QUANTITY	UNIT	MATERIAL	QUANTITY	UNIT
Raw Material Conveying Capacity					
1. Cement			Raw Material Conveying Capacity		
2. Red mud	40,752	tkm		40,752	tkm
3. White Sand					
4. Coarse Aggregate					
			Nitrogen (Nox)	4,7535	kg
Diesel Consumption	1,5	Liters	Carbon Monoxide (CO)	0,0105	kg
			Carbon dioxide (CO2)	0,0765	kg

Source : Data Processing (2025)

b) *Concrete Mixing*

The concrete material mixing process uses a TCM-200L mixer with a power of 1500 Watts, a rotation speed of 3000 Rpm with a mixing time of about 5 minutes.

Normal Concrete / Use of 0% red mud

- Electricity Consumption = Power x Duration of Use

$$= 1.5 \times 5 \text{ Minutes} = 0.125 \text{ kWh}$$
- Water Usage = 165 liters
- Electrical GHG Emissions = Electricity Consumption x FE Electricity

$$= 0.125 \times 0.87$$

$$= 0.000125 \text{mWh} \times 0.87 \text{ tons/mWh}$$

$$= 0.0001087 \text{ tons}$$

$$= 0.1087 \text{ kg}$$

Table 13 Calculation of Greenhouse Gases (GHGs) Based on References

Source	Year	GHG Emissions (kg) CO ₂ /kWh	Remarks
Ministry of Environment and Forestry (National Average)	2023	0,869	Source: MoEF Document No. P.6/MENLHK/SETJEN/KUM.1/1/2023
PLN Statistics	2023	0,85 - 0,89	Varies per system
IEA	2022	0,875	<i>International Energy Agency</i>
MEMR	2023	0,87	Ministry of Energy and Mineral Resources

2. Life Cycle Inventory Concrete Red Mud 25%

In the production of precast concrete, the author conducts two life cycle analyses (*Life Cycle Analysis*), namely at the stage of delivering raw materials and at the *mixing* stage of concrete.

a) Shipping RAW Material

Delivery of raw materials and concrete mixing/*mixing* Carrying capacity using Pick Up with a carrying capacity of 1200 Kg assumed to be sent from the *Mempawah* landfill *location* to the workshop of PT. Syntegra Techno International with a distance of 18 Km, Diesel Requirement of 12 km/Liter (Mitsubishi L300 Assumption). Shipping is divided per percentage of *red mud usage*.

Red mud usage 25%

- Pick up carrying capacity

$$= \text{Carrying Capacity} \times \text{Distance Traveled}$$

$$= 1,2 \text{ ton} \times 18$$

$$= 21,6 \text{ tkm}$$

- Raw material conveying capacity

$$= \frac{\text{Amount of Raw Materials}}{\text{Carrying Capacity}} \times \text{Pick up carrying capacity}$$

$$= \frac{2275,67}{1200} \times 21.6 \text{ tkm}$$

$$= \frac{2275,67}{1200} \times 21.6$$

$$= 40,962$$

- Diesel Consumption

$$= \text{Fuel (Diesel) Requirement} \times \text{Travel Distance}$$

$$= 1/12 \times 18$$

$$= 1,5 \text{ Liter}$$

Table 14 Life Cycle Inventory (LCI) Red Mud Concrete 25%

CONCRETE WITH THE ADDITION OF RED MUD 25%					
INPUT			OUTPUT		
MATERIAL	QUANTITY	UNIT	MATERIAL	QUANTITY	UNIT
Raw Material			Raw Material		
Conveying Capacity	40,938	tkm		40,938	tkm
1. Cement					

2. Red mud		Conveying		
3. White Sand		Capacity		
4. Coarse Aggregate				
Diesel Consumption	1,5	Liters	Nitrogen (Nox)	4,7535 kg
			Carbon Monoxide (CO)	0,0105 kg
			Carbon dioxide (CO2)	0,0765 kg

Source : Data Processing (2025)

b) Concrete Mixing

The concrete material mixing process uses a TCM-200L mixer with a power of 1500 Watts, a rotation speed of 3000 Rpmm with a mixing time of about 5 minutes.

Use of red mud 25%

- Electricity Consumption = Power x Duration of Use
= 1.5 x 5 Minutes
= 0.125 kWh
- Water Usage = 127.26 liters
- Electrical GHG Emissions = Electricity Consumption x FE Electricity
= 0.125 x 0.87
= 0.000125mWh x 0.87 tons/mWh
= 0.0001087 tons
= 0.1087 kg

b. Interpretation

In this study, in the production process of precast concrete, there are three main outputs at the *Life Cycle Impact Assessment stage*, namely *network*, *characterization*, and *single score*. The three outputs are used to display the results of the environmental impact analysis, so that it can determine the largest impact categories and the overall impact value of the process.

1. Network

In the network section, a visualization in the form of a sun key diagram is displayed that shows the contribution of the process to environmental impact based on the thickness of the arrow. The results of the normal concrete diagram show that cement materials make the largest contribution with a value of around 12 Pt, followed by White Sand of 4.14 Pt and W.M Sand of 2.33 Pt. Meanwhile, the results of the red mud concrete diagram of 25% of the diagram can be seen that the largest impact contribution comes from *Cemen* material with a value of around 10.3 Pt, then followed by *White Sand* of 4.14 Pt, and *W.M Sand* of 2.33 Pt. These findings show that cement is the most dominant component of the total environmental impact on the analyzed system.

Product: Pembuatan Beton dengan 0% red mud
 Project: Concrete, with 0% red mud / Conventional
 Category: Assembly/Others
 Method: Eco-indicator 99 (H) V2.10 / Europe EI 99 H/A
 Selected Indicator: Single score, (Pt)
 Indicator mode: Indicator contribution
 Exclude long-term emissions: No
 Node cut-off: 0,631 %

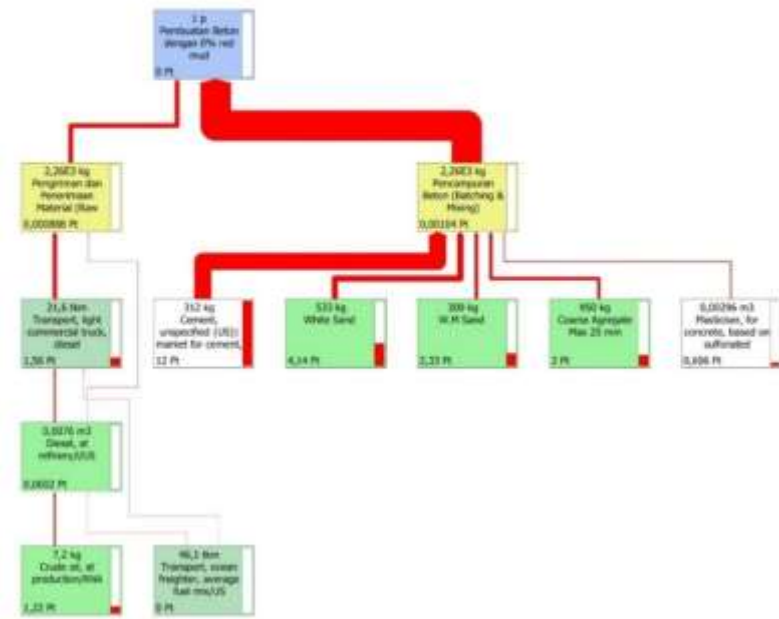


Figure 4 Indicator Contribution on Normal Concrete

Source: Author's analysis using SimaPro software (Eco-indicator 99 method), 2025

SimaPro 10.1.0.2 Network Date: 12/01/2026 Time: 21:32:58
 Project: Concrete, with 25% red mud

Product: Pembuatan Beton dengan 25% red mud
 Project: Concrete, with 25% red mud
 Category: Assembly/Others
 Method: Eco-indicator 99 (H) V2.10 / Europe EI 99 H/A
 Selected Indicator: Single score, (Pt)
 Indicator mode: Indicator contribution
 Exclude long-term emissions: No
 Node cut-off: 2,91 %

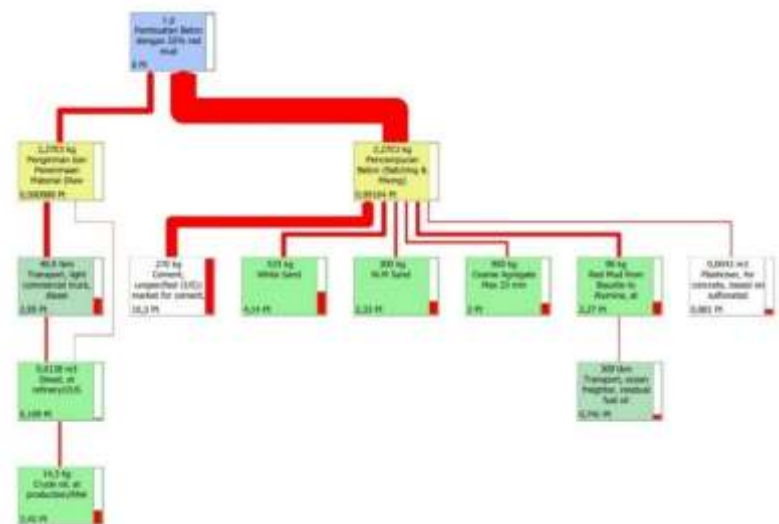


Figure 5 Indicator Contribution on Red Mud Concrete 25%

Source: Author's analysis using SimaPro software (Eco-indicator 99 method), 2025

2. Characterization

In the characterization display, the Eco-indicator 99 (E) method has eleven categories of environmental impacts, namely: (1) Carcinogens that describe carcinogenic potential;

(2) Respiratory organics that show respiratory distress due to organic pollutants; (3) Respiratory inorganics related to particulate matter or inorganic gases that cause respiratory distress; (4) Climate change that contributes to global warming; (5) Radiation that reflects the risk of radioactive exposure; (6) Ozone layer that shows the potential for ozone layer damage; (7) Ecotoxicity which describes the toxic impact on organisms on the ecosystem; (8) Acidification/Eutrophication related to increasing acidity and nutrientification in soil and water; (9) Land use that reflects changes in land use and its implications for the environment; (10) Minerals that indicate the level of consumption of mineral resources; and (11) Fossil fuels associated with the depletion of fossil-based energy resources.

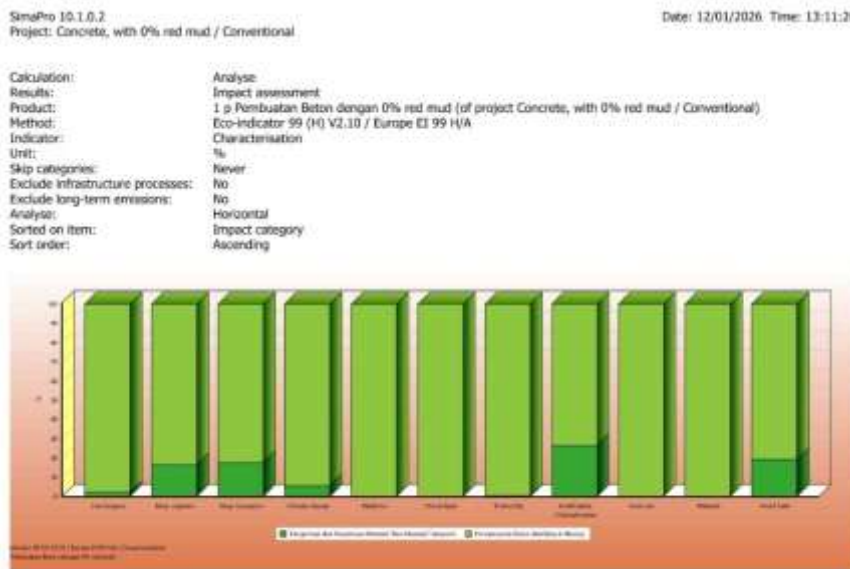


Figure 6 Normal Concrete Impact Assessment Result
 Source: Author's analysis using SimaPro software, 2025

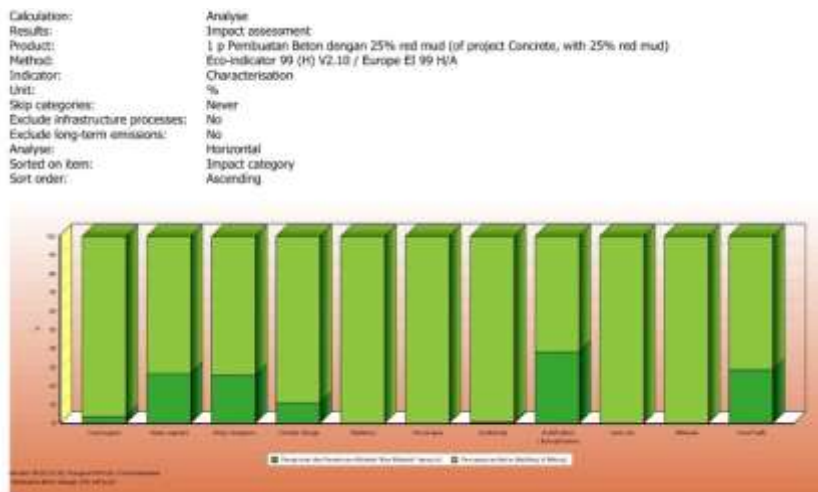


Figure 7 Result Impact Assessment Concrete Red Mud 25%
 Source: Author's analysis using SimaPro software, 2025

3. Single Score

Single *score* analysis was used to see which categories contributed the most overall environmental impact. This method combines the assessment results of various impact categories into a single final value to facilitate the interpretation process.

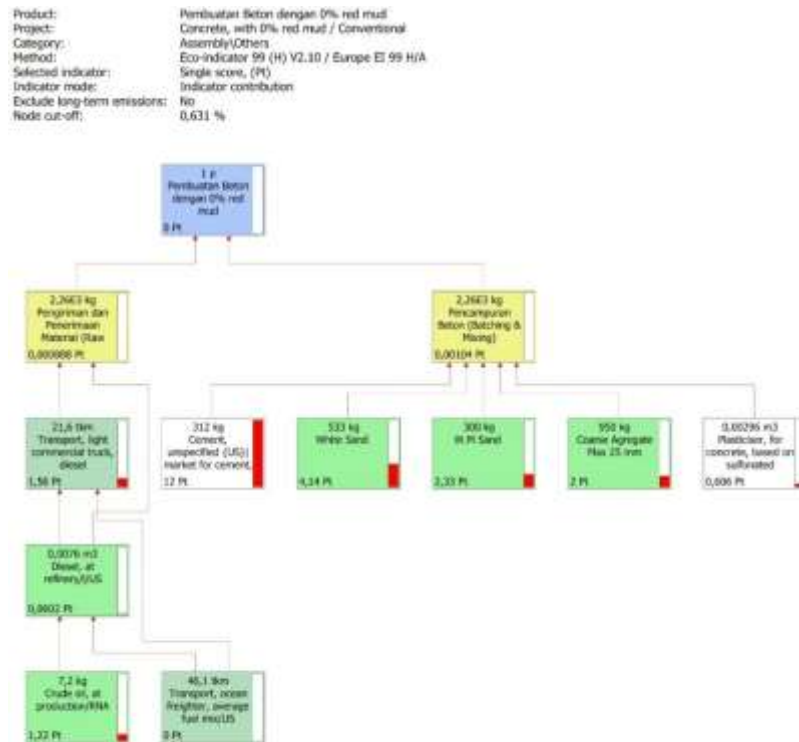


Figure 8 Single Score Normal Concrete

Source: Author's analysis using SimaPro software, 2025

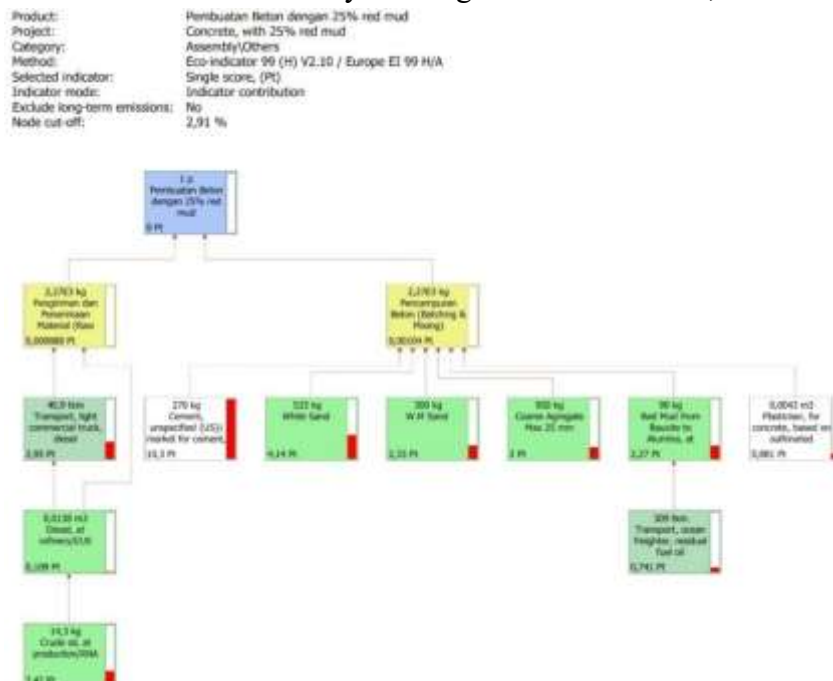


Figure 9 Single Score Red Mud Concrete 25%

Source: Author's analysis using SimaPro software, 2025

Based on the goal score diagram, it can be seen that *the cement* category contributes the highest impact with a value of around 12 Pt on normal concrete, while in the 25% red mud concrete diagram, it can be seen that the *cement category* contributes the highest impact with a value of around 10.3 Pt. These findings show that the use of cement is still the most significant source of emissions to the total environmental impact of the systems analyzed using SimaPro.

CONCLUSION

The use of red mud in this study proves that red mud waste can be used as a partial substitution of cement in concrete, especially in precast products such as paving blocks, without interfering with the production process or rheological properties of concrete, so it is feasible to be applied as an alternative material in construction. The compressive strength performance of the red mud formulation of 25% resulted in a compressive strength of 36.93 MPa at 30 days of age, higher than normal concrete of 34.15 MPa, thus proving that technically 25% red mud meets and even exceeds the performance of conventional concrete. Potential for waste absorption In a paving block production scale of 5,000 m² per year, the 25% red mud formulation is able to absorb up to 41.8 tons of waste per year, thus potentially supporting efforts to reduce bauxite residues that have accumulated in landfills. In terms of economic feasibility, the use of red mud is considered feasible because it produces lower production costs and shows positive economic indicators with an NPV of > 0, BCR > 1, and an IRR of 43.9%, so it has prospects for industrial implementation. The results of the Life Cycle Assessment (LCA) strengthen these findings by showing a decrease in environmental impact, especially in the category of climate change or potential global warming, due to reduced cement consumption. In the analysis of the network, characterization, and single score, it can be seen that the contribution of the environmental impact of cement materials has decreased from about 12 Pt in normal concrete to about 10.3 Pt in 25% red mud concrete, so that this formulation has been proven to be more environmentally friendly. Thus, the use of red mud not only improves technical and economic performance, but also contributes to reducing emissions and supporting the implementation of Sustainable Construction Management (SCM) in the construction industry in Indonesia.

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