Eco-efficiency index analysis of single story structure of reinforced concrete house using economical and environmental score approach

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Abstract. Reinforced concrete structure is widely used in Malaysia as a common structural system of a building. As a common understanding, reinforced concrete is also known as a composite structure that combined two type of materials which is concrete and steel. Due to rapid development of residential houses, this situation was creating to higher energy consumption by producing high content embodied carbon emission Therefore, three main criteria should be considered in sustainable development that is economic, environment and social in order to produce better environment. This study was developed to produce eco-efficiency design of single story residential house for different optimization of concrete characteristic strength by using economical score and environmental score analysis method. Finding was recorded blast furnace slag reinforced concrete produce an eco-efficiency design than fly ash reinforced concrete due to positive impact to the economical and environmental criteria. Therefore, it can be concluding that waste materials need to be analyzed as an alternative material in concrete because it may produce high content of embodied carbon that give negative impact to the environment.

1. Introduction
Rapid development of residential houses in the world was creating to higher energy consumption by producing high content embodied carbon emission [1]. Building construction sector consumed more than one third of total energy used and greenhouse gas emission and it is about 2236 metric tons carbon emission (39 percent) of total emission [2]. According to an annual report of United State Green Building Council (2013), construction building has contributed more than 40 percent carbon emission compared with the industrial and transportation sector. Therefore, it was enhanced in producing better building construction by introduced sustainable development by fulfilling optimum impact to three main criteria which are economic, environment and social [3-4]. Other than that, new approach has been developing to fulfill the environment needs which is green building. There are several green building ratings that have established among the different countries such as Leadership in Energy and Environmental Design (LEED) in United States, Green Mark method in Singapore, Building Research Establish Environmental Assessment Method (BREEAM) in United Kingdom and Green Building Index (GBI) in Malaysia. This rating is necessary in order to know the performance of
building based on the criteria that already state in green building rating system. Therefore, in order to satisfy the term of economic and environment, the eco-efficiency design of reinforced concrete structure is proposed in this study to establish low carbon emission designs with optimum cost and fulfill needs of society. Assessment of eco-efficiency is done by calculating the cost and carbon dioxide emission of normal concrete with alternative concrete that signify the reduction ratio [5]. Comparison of alternative materials in application of building design (morphologies and technical choices) will help the decision-making process to reduce environmental impacts of building and urban projects. In this study, eco-efficiency index method was used to produce excellent performance of building that reducing the environmental impact, enhance the economic and ensure accomplishment of the social quality that focused on structural elements. This study produces an analysis of economical and environmental impact of structural elements of single story house by using fly ash and blast furnace slag as an alternative cement material to promote sustainable reinforced concrete structure design. Besides that, it may benefit to the designer where it provides guidance on improvement of construction method and produce the design that diminish the carbon emission content [6].

2. **Analysis of Eco-efficiency Index of Reinforced Concrete Structure**

Analysis of the reinforced concrete single-story residential house was focused on the structural element consists of foundation, slab, beam and column using two types of alternative concrete materials which is fly ash (FA) concrete and blast furnace slag (BFS) concrete with 15% amount as cement replacement materials [7]. Figure 1 shows the overall flows of eco-efficiency index analysis method of reinforced concrete structure.

![Flow chart determination of eco-efficiency index](image)

Determination of Cost and Carbon Emission of the reinforced concrete material

\[
\text{Cost,ori} = \text{Cost,m} + \text{Cost,c}
\]
\[
\text{CO}_2\text{ori} = (Q_c + Q_s) \cdot \text{EF}_{RC} \quad [8]
\]

Eco. Score (ECOs) = \frac{(\text{Cost,alt} - \text{Cost,ori})}{\text{Cost,ori}}

Env. Score (ENVs) = \frac{(\text{CO}_2\text{alt} - \text{CO}_2\text{ori})}{\text{CO}_2\text{ori}}

\[
\text{Determination of eco-efficiency} \quad [5]
\]
\[
\text{ECO}_{\text{eff}} = \frac{|A X_i + B Y_i|}{(A^2 + B^2)^{1/2}}
\]

**Figure 1.** Flow chart determination of eco-efficiency index.

20 cases of reinforced concrete designed for single story house was used in this study by optimize the characteristic strength of concrete. This is the parameters was taken into consideration because it will differ the amount of concrete volume and steel weight of the structural elements that lead to determine the equivalent carbon emission of the structure.

2.1 **Determination of structural work cost**

The original cost (Cost,ori) is total cost for the material cost (Cost,m) of the normal concrete and the construction cost (Cost,c) that is used in the design as shown in Equation 1. The reinforced concrete design process of the structure determines the quantity of the materials used. The quantity of the material should be separated in term of concrete grade and diameter of steel reinforcement.
\[ \text{Cost,ori} = \text{Cost,m} + \text{Cost,c} \] (1)

The material cost (Cost,m) is calculated by summation of concrete material cost and steel material cost. The formula in determining the concrete cost (Cost,cm) by multiplying the quantity of concrete (Qci) in cubic meter (m\(^3\)) that is used for the construction with the unit price of concrete (Uci) in ringgit per cubic meter (RM/m\(^3\)). The concrete unit price is referring to JKR20800 standard for schedule of rate and it is not a fixed price due to fluctuating cost in market. Furthermore, the unit price of concrete is different to different grade of concrete. The cost of steel (Cost,sm) is determined by it is multiplying product of quantity of steel (Qsh) in kilogram (kg) with unit price of steel (Ush) in ringgit per kilogram (RM/kg). The unit price of steel is also depending on the steel reinforcement diameter that is used in the design. Each diameter of steel reinforcement will give different unit price of that material.

The construction cost (Cost,c) is a summation of concreting work (Cost,cw) and steel work (Cost,sw). The general formula for cost of concrete work is determine by summation of concreting work for foundation (Cost,cf), concretion work for ground floor (Cost,cg) and concreting with for other floor (Cost,cst). The cost of steel work (Cost,sw) is shown by summation of steel work cost for each type of steel reinforcement used in the construction which is depending on the steel reinforcement diameter.

The alternative cost (Cost,alt) is the total cost of the material used which is including alternative material in the concrete. The general formula for alternative cost is shown in Equation 2. The alternative cost is summation of the alternative material cost (Cost,am) and the construction work cost (Cost,c).

\[ \text{Cost,alt} = \text{Cost,am} + \text{Cost,c} \] (2)

The alternative material cost (Cost,am) is a summation of concrete cost (Cost,c), new material cost (Cost,nm) and steel cost (Cost,s). The calculation of alternative material cost is needs to consider the new material amount that is used as a construction material. Therefore, the unit price of the new material that is added in the concrete design should be referring to the current market prices. Besides that, the current standard by the government should be referring in order to avoid discrepancies of the construction cost.

2.2 Determination of equivalent carbon emission
The evaluation of the environmental condition needs to take place in order to ensure the environmental protection will give a better future of the earth. The evaluation of the environmental condition is based on the carbon emission that is produced by the human activities because it was contributed the largest amount of carbon emission in the world. Therefore, Equation 3 shows the general formula of equivalent carbon emission calculation.

\[ \text{CO}_2,\text{ori} = \left( Qci + Qsh \right) \cdot \text{EF}_{\text{RC}} \] (3)

The emission factor of reinforced concrete (\( \text{EF}_{\text{RC}} \)) is a total coefficient of carbon emission of concrete and steel that is produce in the process. The emission factor of concrete (\( \text{EF}_c \)) is refer to ICE Document Version 2.0 and the values is depending on the concrete grade design. Furthermore, the emission factor of steel (\( \text{EF}_s \)) that need to referred ICE Document Version 2.0 is per 100 kilogram emission. Therefore, the emission factor of steel needs to multiply with the amount of steel weight (kg) per concrete volume (m\(^3\)).

The alternative carbon dioxide emission (\( \text{CO}_2,\text{alt} \)) is determine by the product of alternative material quantity with emission factor of reinforced concrete as in Equation 4. The material quantity is
summation of quantity of normal concrete (i) with alternative material in kilogram (kg) and quantity of steel (h) in kilogram (kg).

\[
CO_2,alt = (Qca + Qsh) \cdot EF_{RC}
\]

(4)

2.3 Determination of economical and environmental score

Determination of economic score is the calculation of the reinforced concrete work cost that involved material cost and work cost. In Malaysia, the construction cost should be referring to Schedule of Rate (SOR) by Department of Work Malaysia (JKR20800) [10]. The SOR is differing based on amendment of the policy and also fluctuating of the material cost respect to the market concern. Equation 5 shows the calculation to determine the Economic Score (ECOs) of the reinforced concrete structure in this model that shows the reduction ratio of cost.

\[
ECOs = \frac{(\text{Cost,alt} - \text{Cost,ori})}{\text{Cost,ori}}
\]

(5)

Therefore, the evaluation of the environmental condition needs to take place in order to ensure the environmental protection will give a better future of the earth. The evaluation of the environmental condition is based on the carbon emission that is produced by the human activities because it was contributed the largest amount of carbon emission in the world. Therefore, Equation 6 shows the general formula of environmental score (ENV, s) that shows the reduction carbon emission volume of the normal structural design and alternative structural design.

\[
ENV, s = \frac{CO_2,alt - CO_2,ori}{CO_2,ori}
\]

(6)

2.4 Determination of eco-efficiency index

The eco-efficiency index is developed to determine the best design. Higher value of eco-efficiency index will produce most economical design with low impact on the environment that produces low carbon dioxide emission [5]. The values for economic weight and environmental weight should be consistent either 1 or 2 based on the case situation.

In this study, an integrated model for analyzing the cost and CO₂ emission that is capable of supporting the decision-making process in selecting the most economical and eco-efficiency design in designing reinforced concrete structure was proposed. The Eco-efficiency Index Model that analyzed the cost and CO₂ emission of different reinforced concrete design was framed into three phases which are analysis of the construction cost and CO₂ emission of the design alternatives, calculation of the economic and environmental scores which signify the cost and CO₂ emission reduction ratios respectively based on the previous assessment and selection of the best design alternative based on these two scores.

Further evaluation is being made by determine the eco-efficiency index (ECOeff). Eco-efficiency index is the method to determine sustainable design of reinforced concrete structure based on the economic score and environmental score. In this study, to determine the best design because it is also using the same parameter on economic score and environmental score was adopted [5]. Therefore, Equation 7 determines the eco-efficiency index. The index is calculated to shows the efficiency of the design based on the economic score ration and environmental score ratio that has been calculated.

\[
ECOeff = \frac{|AXi + BYi|}{(A^2 + B^2)^{1/2}}
\]

(7)

Where:

- Xi = economic score for each structural-design alternative
\[ Y_i = \text{environmental score for each structural-design alternative.} \]
\[ A = \text{weight of the economic score} \]
\[ B = \text{weight of environmental score} \]

3. Results and discussion

Results were obtained on analysis of reinforced concrete design for 20 cases single story reinforced concrete house. It was identified to determine most eco-efficiency design of single-story house that lead to low impact to the environment with optimum structural work cost.

3.1 Total structural work cost

Total structural work cost was calculated based on total cost of the structural elements of single story reinforced concrete house including slab, beam, column and foundation. The amount of the total cost recorded was compared between normal reinforced concrete, fly ash reinforced concrete and blast furnace slag reinforced concrete. Determination of total structural work cost is important as main input to determine the economical score of the reinforced concrete structure where normal concrete cost as an original cost and another two alternatives concrete as alternative costs.

![Figure 2. Total structural work cost of reinforced concrete single-story house.](image)

Figure 2 shows the overall total structural work cost of reinforced concrete single-story house for 20 cases as stated for this study. In overall analysis, it was found that alternative reinforced concrete produce lower structural work cost compares with normal reinforced concrete because all of the alternatives material which is fly ash and blast furnace slag was determine as by-product material that produce zero cost of production. It proves that by using waste material it produces positive impact in term of economic as the needs of sustainable development criteria.

Based on economical score, Case 2 with combination of slab (25MPa), beam (30MPa), column (30MPa) and foundation (30MPa) produce high economical impact compare with all other cases. This combination of characteristic strength of concrete is suitable to produce an optimum cost of reinforced concrete eco-efficiency structure. Cost of structural work has been identified from the analysis depending on the sources of alternative materials and amount of the materials used in the structural systems. Furthermore, the different values between each case will be higher if there is overdesign structure in reinforced concrete design. It is because it will produce high volume of materials that
automatically increase the structural work cost. Hence, optimization of structural element parameters is very important in order to control the volume of materials.

3.2 Total equivalent carbon emission

Total equivalent carbon emission was calculated as an input parameter for environmental score ratio. The total equivalent carbon emission is important parameter that needs to be counting to fulfill environmental factor of sustainable development criteria. It is referred to amount of carbon emitted from the structural element of the building that may contribute to high concentration of carbon in the atmosphere, as we know that it may affect the environment condition.

![Total Equivalent Carbon Emission of Reinforced Concrete Single Story House](image)

**Figure 3.** Total equivalent carbon emission of reinforced concrete single-story house.

Figure 3 shows the total equivalent carbon emission of reinforced concrete single-story house based on Equation 3 for normal reinforced concrete and Equation 4 for alternative reinforced concrete. The result recorded for 20 cases of characteristic strength of concrete combination to produce different level of effectiveness of eco-efficiency. Based on the results, it was analyzed that blast furnace slag reinforced concrete produced low amount of equivalent carbon emission compared to normal and fly ash reinforced concrete. It was found that increasing fly ash content to replace Portland cement corresponding reduction of emission based on it mass. Other than that, fly ash content may effect on embodied water on concrete about 2.7 to 4.1 cubic meter for every cubic meter of concrete [8].

By using blast furnace slag as an alternative material in concrete, it was found that positive impact toward environment and economic recorded because the equivalent carbon content in the materials is low than Ordinary Portland Cement. This material was found suitable as an alternative material to replace cement in concrete with 15 percent of the total amount by controlling the structural elements parameters such as size of the elements, characteristic strength of concrete, and orientation of the structural elements.

3.3 Eco-efficiency index

Table 1 shows the results of eco-efficiency index of single story reinforced concrete residential house where the higher the eco-efficiency index the better the eco-efficiency performance. From the analysis, results found that case 5 (foundation 30MPa, slab 20MPa, beam 30MPa, column 30MPa) shows highest eco-efficiency index either using fly ash or blast furnace slag as alternative materials in concrete. The optimization of characteristic strength of concrete is leading to develop the eco-efficiency design level of the structure. Increasing of the characteristic strength of concrete (5MPa) of
the structural elements was justified about 3 percent increasing of the equivalent carbon emission emitted from the structural elements. Characteristic strength of concrete and steel reinforcement was found as two main parameters that give impact to the amount of carbon emission where higher strength produced high amount of carbon emission. By controlling this parameter, it will differ the impact of economical and environmental factors of the building that lead to determine the eco-efficiency index of the reinforced concrete structure.

| Case | Fly Ash | Blast Furnace Slag |
|------|---------|-------------------|
| ENV | ECO | ECO_eff | ENV | ECO | ECO_eff |
| 1   | -0.0801 | 0.0092 | -0.0501 | 0.0094 | 0.0092 | 0.0132 |
| 2   | -0.0793 | 0.0095 | -0.0494 | 0.0114 | 0.0095 | 0.0147 |
| 3   | -0.0746 | 0.0090 | -0.0463 | 0.0129 | 0.0090 | 0.0155 |
| 4   | -0.0788 | 0.0094 | -0.0491 | 0.0111 | 0.0094 | 0.0145 |
| 5   | -0.0750 | 0.0094 | -0.0463 | 0.0132 | 0.0094 | 0.0160 |
| 6   | -0.0807 | 0.0094 | -0.0504 | 0.0070 | 0.0094 | 0.0115 |
| 7   | -0.0816 | 0.0091 | -0.0512 | 0.0051 | 0.0091 | 0.0101 |
| 8   | -0.0795 | 0.0090 | -0.0562 | 0.0078 | 0.0090 | 0.0119 |
| 9   | -0.0787 | 0.0092 | -0.0492 | 0.0080 | 0.0092 | 0.0122 |
| 10  | -0.0746 | 0.0092 | -0.0462 | 0.0098 | 0.0092 | 0.0134 |
| 11  | -0.0733 | 0.0093 | -0.0453 | 0.0123 | 0.0093 | 0.0152 |
| 12  | -0.0799 | 0.0093 | -0.0499 | 0.0062 | 0.0093 | 0.0110 |
| 13  | -0.0785 | 0.0092 | -0.0490 | 0.0087 | 0.0092 | 0.0127 |
| 14  | -0.0783 | 0.0093 | -0.0488 | 0.0060 | 0.0093 | 0.0109 |
| 15  | -0.0791 | 0.0092 | -0.0494 | 0.0084 | 0.0092 | 0.0125 |
| 16  | -0.0786 | 0.0094 | -0.0490 | 0.0089 | 0.0094 | 0.0129 |
| 17  | -0.0808 | 0.0093 | -0.0506 | 0.0089 | 0.0093 | 0.0129 |
| 18  | -0.0811 | 0.0093 | -0.0508 | 0.0064 | 0.0093 | 0.0111 |
| 19  | -0.0777 | 0.0093 | -0.0484 | 0.0105 | 0.0093 | 0.0140 |
| 20  | -0.0840 | 0.0093 | -0.0528 | 0.0026 | 0.0093 | 0.0084 |

Further finding was recorded blast furnace slag reinforced concrete produce an eco-efficiency design than fly ash reinforced concrete due to positive impact to the economical and environmental criteria. Therefore, it can be concluded that waste materials need to be analyzed as an alternative material in concrete because it may produce high content of embodied carbon that give negative impact to the environment.

4. Conclusion
As for conclusion, in order to ensure the design is fulfilling the needs of eco-efficiency, there are few parameters that need to take into consideration which are characteristic strength of materials, alternative materials sources and design parameters. Based on the overall results, it was found that fly ash reinforced concrete fulfill sustainable criteria compare to blast furnace slag concrete due to positive impact for both parameters. 5MPa different of concrete characteristic strength will impact increasing and decreasing of total eco-efficiency index values that may differ the performance to fulfill requirement of sustainable design. All those considerations will lead to determination of amount for total cost and total equivalent carbon emission that should be consider in analysis of eco-efficiency index. The designer should determine the design parameter based on the structural elements of the building and not to consider for the whole building because the impact in eco-efficiency design is identified different.

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