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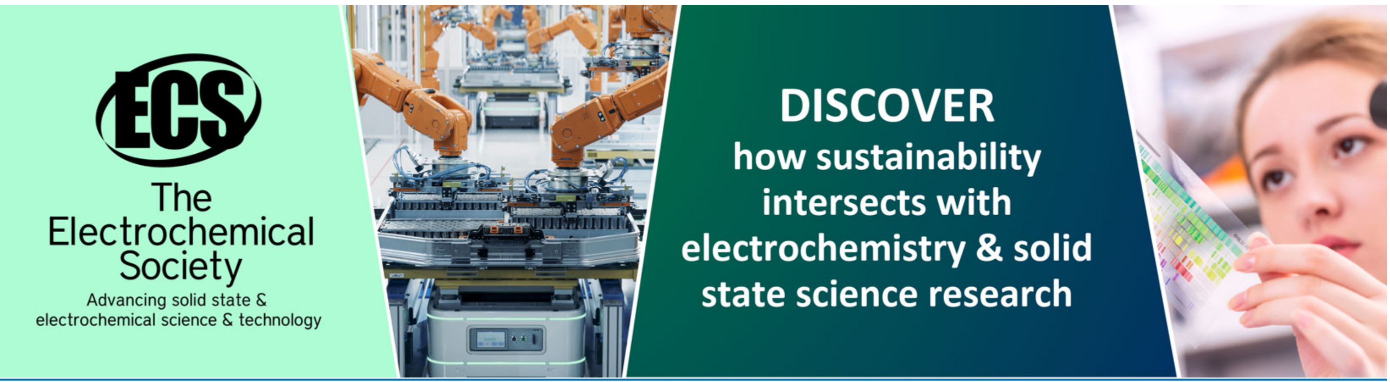

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Eco-durability index of self-compacting concrete incorporating high volume fly ash

S A Kristiawan[1*], **S Sangadji**[1] **and Sunarmasto**[1]

[1]SMARTCrete Research Group, Civil Engineering Department, Universitas Sebelas Maret, Jl. Ir. Sutami No. 36 A Surakarta 57126, Indonesia

[*]Email: s.a.kristiawan@ft.uns.ac.id

Abstract. Designing concrete meeting the principles of sustainability becomes urgent in the construction of buildings and other civil engineering infrastructures. Sustainability of concrete can be assessed by considering its environmental, economic and social impact. Each impact may cover multi-criteria and parameters for the assessment. In this respect, the designers require practical tools so as to select the best alternative concrete mix design fulfilling the multi-criteria. This paper proposed an eco-durability index (*EDI*) as such tool for assessing the balance performance in term of environmental impacts and durability of self-compacting concrete (SCC) incorporating high volume fly ash. The fly ash content is in the range of 50%-70% of replacement level i.e. a fraction of cement replaced by weight of fly ash. The parameters adopted for assessing the environmental impacts (ecological index) are embodied primary natural resources depletion, embodied energy and embodied CO_2; while the time to corrosion initiation period due to chloride ion ingress by diffusion mechanism is taken as durability parameter. The chloride ion diffusions of the concretes under study were determined following ASTM C1556 from the chloride profiles. The chloride profiles were obtained by salt ponding test according to AASHTO T259. The amount of chloride ion with respect to the depth of its penetration was determined by XRF method. Within the scope of this study, it is shown that an increase of fly ash will reduce the environmental impacts of SCC. However, the durability of concrete does not show a similar trend. Therefore, a balance performance considering the environmental impacts and durability is searched for by using the value of *EDI*. Based on the *EDI*, it is indicated that SCC with 70% fly ash replacement level gives the best alternative of SCC with respect to balance performance of environmental impacts and durability.

1. Introduction

Nowadays, sustainability is a major issue in the design and construction of buildings and other civil engineering infrastructures. In this respect, the development and use of construction materials e.g. concrete have to be directed toward complying to the principles of sustainability. The development of concrete from time to time reflects this evolution and direction i.e. from complying to safety; to durability; to service life/functionality; and finally, to sustainability. It should be noted that, firstly, each component in the evolution process is not intended to replace the other component; instead all the components are closely linked to each other's. Secondly, the latest developed component, sustainability, has not only evolved from the previous components, but works as a function of them as well [1].

Assessing the sustainability of concrete may include the following consideration of impact assessments: environmental (ecological), economic and social [2-4]. Ecological impact assessment is related to the consumption of resources and emissions of pollutants during its life cycle; economic impact assessment can be associated with the life cycle cost of raw materials, fuel and energy consumption; while the social impact assessment concerns with the negative impact compensation costs to meet the social needs of individuals: living conditions, medical treatment and health, education and culture as well as necessities of life (including water, food and clothing) [2].

There are many methods and procedures for assessing the environmental impact of a product. ISO 14040 [5] gives an example of such method and procedure. The method may be applied for assessing environmental impact of concrete for the entirely life cycle (cradle to grave) or for particular stages of its life cycle (cradle to gate). ISO 14040 comprises four phases in the Life Cycle Assessment (LCA) study. The sequence of the phases is as follows: a) the goal and scope of definition phase; b) the inventory analysis phase; c) the impact assessment phase; and d) the interpretation phase. However, the standard may be used for Life Cycle Inventory study (LCI study) only. The LCI study is similar to the LCA study but to exclude the impact assessment phase.

The inventory analysis phase of the LCA study is an inventory of input/output data with regard to the system being studied. It involves collection of the data necessary to meet the goals of the defined study. The term input/output can be a product, material or energy flow that enters/leaves a unit process, respectively. In order to obtain accurate and comparable results of the LCI/LCA study, the system being studied must be clearly defined within the system boundary i.e. set of criteria specifying which unit processes are part of a product system. Figure 1 shows an example of system boundary and inventory data for assessing the environmental impact of concrete & concrete structures [6].

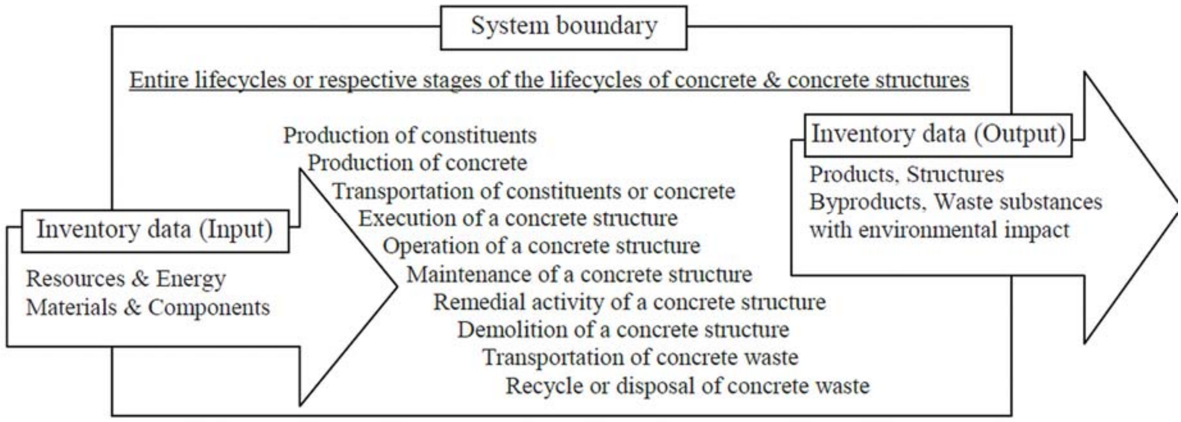

Figure 1. System boundary and inventory data for conducting LCI or LCA of concrete & concrete structure [6].

The result of LCI/LCA study on concrete can be used to directly compare the environmental performance of various concrete mixes; from which the best alternative concrete mix design is selected. However, such comparison and selection are possible if a modification of mix design of the concrete causes parallel trend to all environmental impact indicators. For example, replacing coarse aggregates and cement with recycled aggregates and fly ash, respectively, will reduce the environmental impacts in the same way in term of pollutants emission and energy consumption [7]. On the other hand, if there is a case where changing concrete mix design causes a conflicting trend between the environmental impact indicators, the results -although presented in quantitative manner- can only be used to identify the effect of concrete mixing parameters to the environment with respect to each indicator. Kim et al [8] showed this situation when they studied the influence of recycling components, admixture and compressive strength on the global warming potential, ozone depletion potential, acidification potential, abiotic depletion potential, photochemical oxidant creation potential, and eutrophication potential. Further analysis is required to guide us to directly choose the best alternative concrete mix design by taking into account all the quantitative values of the environmental impact indicators. For this reason, it is necessary to develop, for example, an ecological index by assigning a weighting factor to each environmental impact indicator. Long et al [9] consider the following indicators for assessing the environmental impacts: the amount of primary natural resources (raw material) depletion, energy consumption, and emission of pollutant (CO_2). They showed that the use of fly ash in SCC influences the values of these environment impact indicators in the same direction. Thus, these indicators will be adopted for the current research to form the following ecological index (*EI*):

$$EI=C+E+R \tag{1}$$

where *C, E*, and *R* is the embodied CO_2 (kg/m^3), embodied energy (MJ/m^3), and embodied primary resources (kg/m^3), respectively.

In practice, selecting the concrete mix design that will comply to the principle of sustainability involves various multi criteria. Wang et al [10] proposed a hierarchical life-cycle design of reinforced concrete structures which consists of six levels of design i.e. safety and reliability design (level 1), durability design (level 2), economic evaluation (level 3), local environmental evaluation (level 4), social evaluation (level 5), and global environmental evaluation (level 6). Basically, the selection of alternative concrete mix design by this hierarchical life-cycle design method is as follows: the design begins by choosing the alternatives concrete that comply to the design criteria of level 1; and the selection continues to fulfil criteria of the next level until each design criteria of all levels are met. Thus, the design criteria of each level can be viewed as a filter for continues screening toward obtaining the best concrete meeting the design criteria of all levels. Other approach in selecting concrete toward sustainability is by using eco-mechanical index [9, 11, 12]. The approach basically is an attempt to balance the mechanical and environmental performance. Meanwhile, Kristiawan et al [13] proposed an extension of the eco-mechanical index to include the durability and formed the eco-mechanical-durability index. The durability indicator being used is the sorptivity of concrete. There are many other parameters of durability that could be employed to develop the durability indicator and index. Pillai et al [14] proposed chloride diffusion coefficient as a durability indicator from which the service life of concrete is predicted.

The chloride ions diffusion is governed by the Fick's second law as follows:

$$\frac{\partial c(x,t)}{\partial_t} = D\frac{\partial^2 c(x,t)}{\partial x^2} \tag{2}$$

where *x* and *t* are depth of chloride penetration and time, respectively; *C(x,t)* is concentration of chloride ion corresponding to a depth of *x* at time *t*; while *D* represents chloride ion diffusion coefficient of concrete. The boundary conditions for solving equation (2) are:

$$c(x,t)\begin{cases} c_S \text{ if } x=0 \\ c_O \text{ if } x\approx\infty \end{cases} \tag{3}$$

where C_o and C_s is an initial concentration of chloride ion in the body of concrete and concentration of chloride ion at the concrete surface, respectively. The numerical solution of equations (2) dan (3) by finite difference method has been presented in [15]. The solution covers the influence of temperature and fly ash content as cement substitution in SCC. If the depth of chloride ion penetration *x* equals to the depth of reinforcement and *C(x,t)* corresponds to the critical chloride content C_{cr}, then the solution of the above equations can be used to estimate corrosion initiation time *Ti*. The corrosion initiation time *Ti* may be viewed as the limit of concrete with no maintenance. Other researchers [14] used *Ti* as the limit of service life.

Previous research showed that the use of fly ash as cement substitution can promote environmental friendliness of concretes, either assessed on the basis of environmental impact only [7], or combining environmental impact and mechanical performance (eco-mechanical index) [9], or combining environmental impact, mechanical performance and durability (eco-mechanical-durability index) [13]. This research is further development of eco-durability index that may be used as a tool to select the

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balance performance (between environmental impact and durability) of SCC incorporating high volume fly ash. The durability indicator proposed in the previous research is based on the sorptivity of concrete [13], while for the current research it is based on the chloride diffusion coefficient. It is noted that the latter indicator is not intended to replace the previous indicator. Instead, it gives an alternative option in quantifying the durability performance. The choice of the indicator will depend on the real exposure and mechanism by which aggressive agents penetrate into concrete being assessed.

The formulation of the eco-durability index (*EDI*) for the current research is:

$$EDI = \frac{C\left(\frac{kg}{m^3}\right)}{T_i\left(year\right)} + \frac{E\left(\frac{MJ}{m^3}\right)}{T_i\left(year\right)} + \frac{R\left(\frac{kg}{m^3}\right)}{T_i\left(year\right)} \tag{4}$$

Equation (4) will be applied to identify the influence of fly ash content on combined ecological impact and durability (service life) of SCC incorporating high volume fly ash. Based on the value of *EDI*, the best alternative mix design of SCC can be selected considering the balance performance with respect to environment and durability (service life).

2. Materials and properties of concrete under study

2.1. Materials

SCC was made of the following components: ordinary Portland cement (C), sand (S), coarse aggregate (CA), water (W), superplasticizer (Sp), and fly ash (FA). The mix compositions of the SCC with various fly ash contents are presented in table 1, and their fresh properties are given in table 2.

Table 1. Mix composition of SCC per m^3.

ID	C (kg)	S (kg)	CA (kg)	W (kg)	Sp (kg)	FA (kg)
C50	384	595	710	231	7.68	384
C55	345	595	710	231	7.68	422
C60	307	595	710	231	7.68	461
C65	269	595	710	231	7.68	499
C70	230	595	710	231	7.68	538

Table 2. Fresh properties of SCC.

Test	Parameter	Results				
		C50	C55	C60	C65	C70
Flow Table	diameter (mm)	655	675	720	730	790
J-Ring	diameter (mm)	570	590	675	670	700
V-funnel	time (sec)	13.7	20.8	12.4	11.5	12.4

2.2. Diffusion coefficient

The chloride diffusion coefficient of the SCC was obtained by salt ponding test according to AASHTO T259 [16] where one surface of the SCC specimen (slab) was exposed to solution of 3% NaCl for a period of 90 days. The test started at the age of 28 days after concrete casting. After 90 days of exposure to 3% NaCl, the specimen was core drilled. The sample of the core drilled was then sliced to represent depths of 1, 2, 3, 4, 6, 8, 10, and 12 mm from the exposed surface. The chloride contents at various depths were determined by XRF method. The chloride concentrations and their corresponding depths were then plotted to compose the observed chloride profiles as can be seen in figure 2. The data of observed chloride contents can also be used to predict the chloride profiles following ASTM C1556 [17]. For the current study, the prediction was calculated using L-365 software.

Two important parameters can be obtained from the calculation of chloride profiles i.e. the coefficient of diffusion *D* and its corresponding chloride concentration at the surface of concrete *Cs*. These two parameters are presented in table 3.

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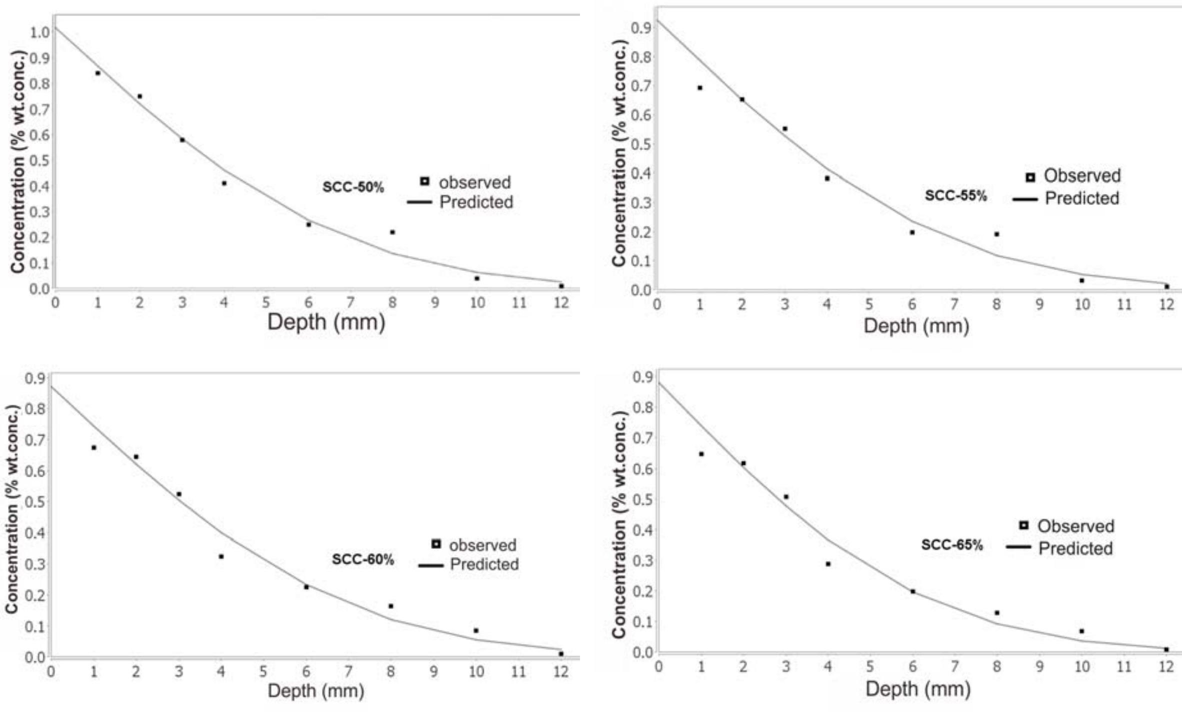


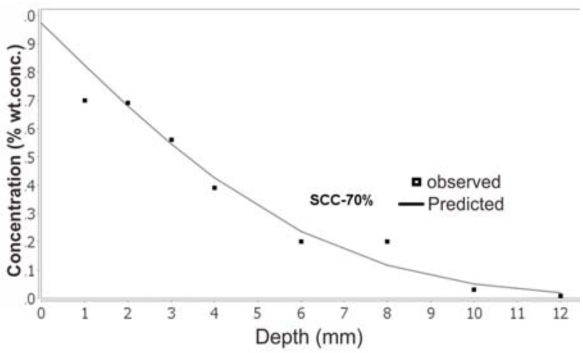


Figure 2. Predicted and observed chloride profile of SCC incorporating various fly ash contents.

Table 3. *D* and *Cs* of SCC with various fly ash contents.

Fly ash content	50%	55%	60%	65%	70%
D (m2/s)	5.90E-12	5.71E-12	6.03E-12	4.99E-12	5.47E-12
Cs (% by weight of concrete)	1.018	0.926	0.872	0.881	0.974

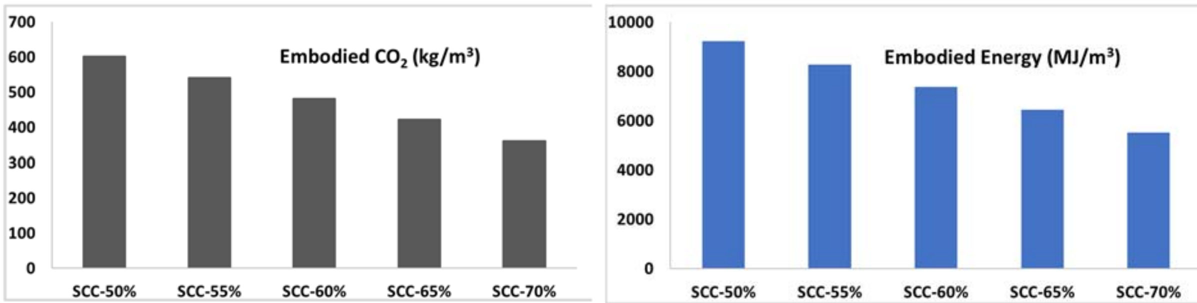
3. Ecological index of SCC

The environmental impact of SCC incorporating high volume fly ash will be assessed by considering three impact indicators i.e. the amount of primary natural resources (raw material) depletion, energy consumption, and emission of pollutant (CO_2). The quantitative values of these indicators for each concrete constituent are taken from [9] and presented in table 4. The values are obtained on the basis of calculating the expenditure of raw natural materials, consumption energy, and emission of CO_2 for producing per m^3 of SCC which includes the following unit processes: extraction of raw materials, transportation to the site, construction processes and so on but not post-installation operations e.g. operation of concrete structure, or demolition, etc. The transportation distance to the site is fixed at 30 km. It is also assumed that after concrete installation, no repair or maintenance is required until the corrosion initiation period *Ti*.

Table 4. The environmental impact indicators of the raw materials of concrete [9].

Items	*C* (embodied CO_2)	*E* (embodied Energy)	*R* (embodied Resource)
	kg/m^3	MJ/m^3	kg/m^3
Cement	0.830	4.727	1.73
Fly Ash	0.009	0.833	0
River Sand	0.001	0.022	1.0
Crushed Stone	0.007	0.113	1.0
Superplasticizer	0.720	18.30	0
Water	0.0003	0.006	0

The environmental impact of SCC incorporating high volume fly ash is calculated directly by considering the amount of each constituent per m^3 with its corresponding environmental impact indicator of table 4. It should be noted that the amount of fly ash introduced in the concrete is simply to partially replace cement by weight. Thus, the difference in the mix composition of SCCs lies in the cement/fly ash ratio, while the other constituents remains the same. Since the density of cement is higher than the density of fly ash, so the total volume of SCC with a higher fly ash content will be higher than that of SCC with a lower fly ash content. However, the difference of this volumetric concrete is omitted in this study. The influence of fly ash on each environmental impact indicator is presented in figure 3. The results clearly show that incorporating fly ash can reduce the environmental impact of SCC in term of either the amount of primary natural resources (raw material) depletion, energy consumption, or emission of pollutant (CO_2). The higher the amount of cement replaced by fly ash, the higher the reduction is. Thus, fly ash reduces all the environmental impact indicators in the same direction.



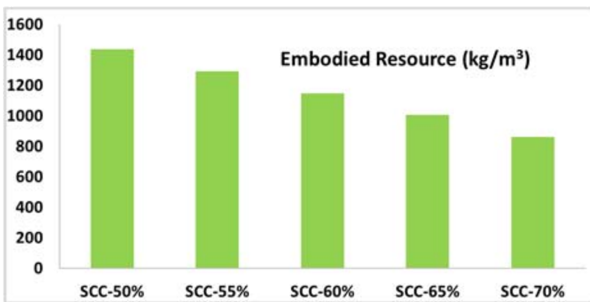


Figure 3. Environmental impacts of SCC incorporating high volume fly ash.

4. Eco-durability index of SCC

The eco-durability index (*EDI*) of SCC will be assessed using equation (4). Hence, the first step to calculate the *EDI* is by determining the values of environmental impact indicators and the time to corrosion initiation period T_i. The former values have been presented in section 3. This section briefly describes the procedure for determining the T_i and subsequently the *EDI* of SCC. To determine the T_i, the following assumptions are made:

- Coefficient diffusion is a function of both time (t) and temperature (T) as shown by the following equation:

$$D_{(t)} = D_{(ref)} \left(\frac{t_{(ref)}}{t} \right) m \tag{5}$$

$$D_{(T)} = D_{(ref)} \exp\left[\frac{U}{R} \left(\frac{1}{T_{(ref)}} - \frac{1}{T} \right) \right] \tag{6}$$

where $D_{(t)}$, $D_{(T)}$, $D_{(ref)}$ is coefficient diffusion at time t, coefficient diffusion at temperature T, coefficient diffusion at $t_{(ref)}$ and $T_{(ref)}$, respectively

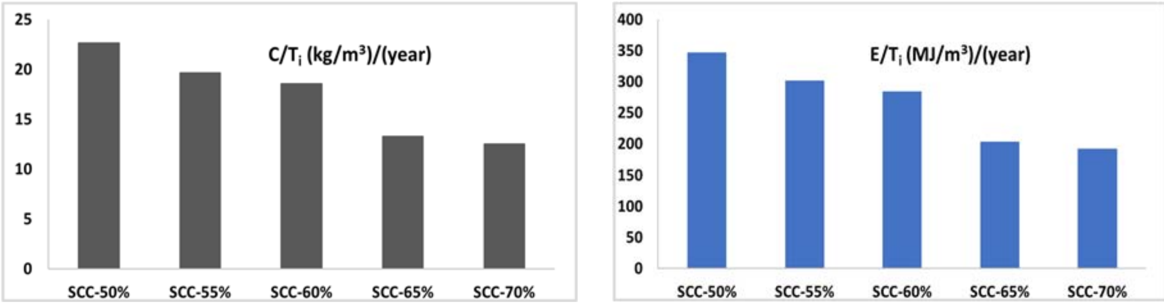
- $t_{(ref)}$ is 28 days and $T_{(ref)}$ is 293 K (20ºC).
- m is diffusion decay index and taken at constant value of 0.5
- Equation (5) is only valid up to 25 years, after which the $D_{(t)}$ equals to $D_{(25\ years)}$
- Coefficient diffusion of SCC presented in table 3 is taken as $D_{(ref)}$
- U and R is activation energy of the diffusion process (35000 J/mol) and gas constant, respectively
- The monthly temperature thorough the year is typical of the Indonesian climate
- Maximum concentration of chloride ion at the surface of concrete C_s for each SCC is given in table 3 and this max concentration is achieved after 10 years of exposure
- Critical chloride concentration to initiate corrosion C_{cr} is 0.06 kg by weight of concrete
- Chloride ion penetrates into concrete through one surface only
- The concrete cover is 60 mm

The numerical solution of equation (2), equation (3), equation (5) and equation (6) have been carried out using the Life-365 software and the results of the time to corrosion initiation period T_i are given in table 5. The table indicates that the service life of SCC incorporating high volume fly ash is in the range of 25.9 to 31.8 years. SCC-60% has the lowest service life while SCC-65% has the longest service life. No general trend can be deduced to indicate the influence of fly ash content on the corrosion initiation time T_i.

In the preceding section, it has been suggested that SCC-70% is the most environmentally friendly concrete among other alternatives of SCC. All the environmental impact indicators justify this conclusion. However, the service life of SCC-70% is below that of SCC-65%. To choose the best concrete with a balance performance in term of environmental impact and durability (service life), this paper proposed *EDI* where the value can be calculated using equation (4). The results of *EDI* is presented in figure 4. It is clearly shown that in spite of lower service life than SCC-65%, but overall SCC-70% gives a better performance with respect to *EDI*.

Table 5. Time to corrosion initiation of SCC.

Concrete	SCC-50%	SCC-55%	SCC-60%	SCC-65%	SCC-70%
T_i (years)	26.6	27.5	25.9	31.8	28.8



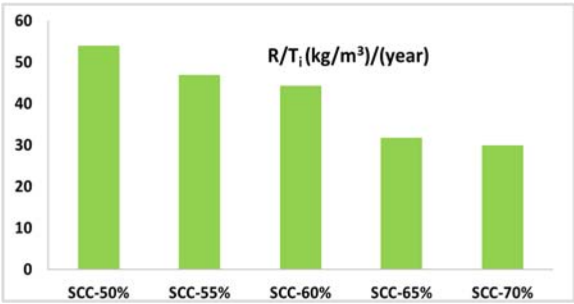


Figure 4. Eco-durability index of SCC incorporating high volume fly ash.

5. Conclusions

Designing concrete that comply to the principles of sustainability can be assisted by practical tools. This paper proposed an eco-durability index (*EDI*) that can be used to select the best alternative concrete by considering the balance performance with respect to environmental impacts and durability. The parameters adopted for assessing the environmental impacts (ecological index) are embodied primary natural resources depletion, embodied energy and embodied CO_2; while the time to corrosion initiation period due to chloride ion penetration by diffusion mechanism is taken as the durability parameter.

Five mix compositions of SCC incorporating high volume fly ash have been selected for the purpose of illustrating the use of the *EDI*. Within the scope of this study, it is suggested that increasing fly ash content will reduce the environmental impacts of SCC. All the environmental impact parameters show this case. However, in term of durability, no such trend is obtained. It is indicated that SCC-65% gives a longest service life compared to other SCCs. To select the best alternative of SCC with a balance performance of environmental impacts and durability, value of *EDI* is used. The *EDI* suggests that SCC-70% is the best alternative of SCC.

Acknowledgments

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