SUSTAINABLE CONCRETE INDICATORS AND THEIR RELATION WITH THE SUSTAINABLE DEVELOPMENT GOALS

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1. Introduction

For global sustainability to be realized, the collective effort of the government, private sectors, and general public is needed. This is the main theme encouraging the concrete sector to integrate the principles of sustainability into its engineering discipline. However, the concept of sustainability has always been elusive since its inclusion into concrete and reinforced concrete since the 2000s because of the dilemma in translating it into quantifiable terms. There are several attempts and methodologies proposed in both research and practice addressing this issue, but consensus has not been fully reached. For instance, Henry & Kato (2012)[1)] operationalized the use of sustainability indicators (SIs) to translate the different perspectives on sustainability of the Japanese concrete industry into practice and material creation.

ISO 21929 (2011)[2)] defined indicators as figures or other measures that enable information on a complex phenomenon, like environmental impact, to be simplified into a form that is relatively easy to use and understand. Indicators have three main functions: quantification, simplification, and communication. The use of indicators became a universal yardstick in dealing with evaluations relevant to sustainability. For example, an indicator-based approach underpinned the major global assessment of countries progress towards Millennium Development Goals and more recently towards Sustainable Development Goals (SDGs)[3)]. In the recent decade, there has been an explosion in the number of sustainable concrete indicators (SCI) proposed in research following an industry-wide call for sustainability.

The initial work by the authors produced an aggregate list of 65 indicators with a structure modeled according to the widely recognized pillars of sustainability – the environment, economy and society[4)]. Further developments arising from this work have resulted in a causal structure of indicators - showing the driving force, state and impact indicators - clarifying the dependency and interrelationships of the SCIs. While these are valuable outputs it is still unclear whether the use of these sustainable concrete indicators has a global impact, which should be the main force diving why they are proposed and used: to contribute to the international cause for a sustainable future and to achieve sustainability in general.

In this paper, the discussion focused on clarifying if the SCIs have a global perspective. This is made clear by determining the relationship of the indicators to the universally accepted Sustainable Development Goals. The SDGs are the proper benchmark to justify that the local efforts being made in the concrete sector through the SCIs contribute towards international sustainability. The SDGs themselves aside from having global reach, are timely and have clear targets. A demonstration study is presented to illustrate that the SCI-SDG relationship can be quantified using the values of each indicator and how their individual behavior influence the SDGs.

2. SCI and the Sustainable Development Goals

2.1 The Sustainable Development Goals

The Sustainable Development Goals (SDGs) are a relatively new plan of the United Nations in its recognition and appreciation for a continued push for a sustainable future, with – in accordance with the words of the UN – supremely ambitious and transformational vision, particularly to free the world from poverty, hunger, and disease. The SDGs are composed of 17 goals, each of which has a particular set of targets to achieve by 2030. The SDGs and targets are integrated and indivisible, global in nature, and universally applicable, taking into account different national realities, capacities, and levels of development while respecting national policies and priorities[5)]. These targets are designed so that each government can set their own national targets in a national declaration, such as the Intended Nationally Determined Contribution (INDC). Different sectors such as construction can be guided in their direction and focus on resolving sectoral intrinsic sustainability issues following the INDC. The international undertakings for sustainability expressed through the SDGs can be funneled down and differentiated towards sectoral or industry targets like an inverted pyramid pattern. The idea is that the SDGs will be achieved through the unified effort of everyone.

Since its ratification in September of 2015, the SDGs still remained unpopular and difficult to incorporate amongst government processes, to the practices of private sector, and to the general public behavior. One barrier pointed out is the low awareness[6)], and the targets themselves lack a framework with which different sectors and industry operations can easily work. Despite this minor shortcoming of the overall SDG framework, the goals remain as a guide to scale up sustainability move exercised by any government, private, and sectoral groups. In this paper, to elevate the importance of the sustainable concrete indicators, their contribution and relation to the SDGs is made clear.

2.2 Relation of the SCIs to the SDGs

The SDGs themselves are broad concepts, but with the associated set of targets serving as the backbone for each goal, the operationalization of the SDGs can be clearly defined. There are 169 targets distributed amongst the 17 sustainable development goals. The SDGs' targets are the key structural basis upon which the authors relate the sustainable concrete indicators and the internationally defined goals. One of the tools utilized to find the relation of the SCIs and the SDGs is the description of each indicator.

Mutual similarity between the SCIs and each targets were found by individually matching the indicator's definition and the statement of each target. Take, for instance, the indicator 'Recycled, Recovered or Waste Materials Content' (both pre and post-consumer), briefly defined as the amount of recycled materials used in the concrete matrix, which has mutuality with the objectives of several targets, as shown in Figure 1. The thematic concept of waste utilization, recycling and resource efficiency is prevalent in SDG targets 6.3, 9.4, 11.6, 12.2 and 12.5, exhibiting that some of the SCIs are relevant to not only one specific target, but transcend to many other

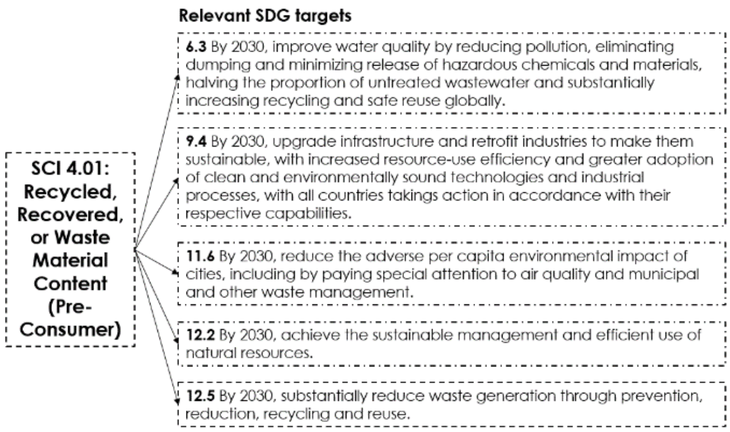

Figure 1 Sample indicator matching with the SDG targets

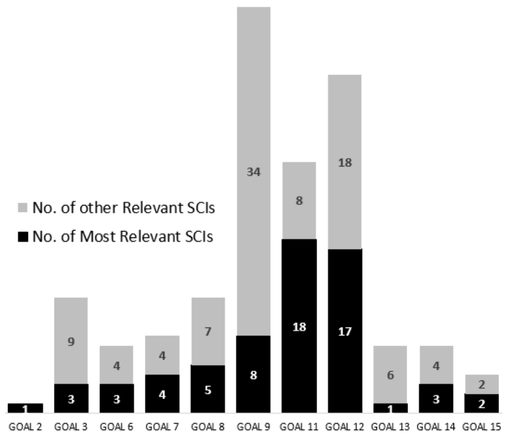

Figure 2 Distribution of the SCIs to their relevant SDGs

related targets of various goals. In this example, by critically examining the targets, it can be concluded that the SCI 4.01 is directly and most relevant to target 12.5. Consequently, this particular indicator is most relevant to Goal 12 to 'Ensure sustainable consumption and production patterns,' which target 12.5 is part of. However, since it is also relevant to targets 6.3, 9.4, and 11.6, this means that this indicator can also contribute to the attainment of Goal 6, Goal 9 and Goal 11.

By repeating the process of matching and finding mutual similarity between the sustainable concrete indicators and the targets of the SDGs, we found the distribution, shown in Figure 2, of the 65 disaggregated SCIs into their respective sustainable development goals. It can be observed from the same figure that the indicators are only particularly relevant to 11 SGDs and not to all 17 SDGs. Figure 2 also shows the number of indicators most relevant to, as well as the number of indicators that are relatively relevant to, a particular SDG. In this distribution it is evident that the sustainable concrete indicators are most relevant to Goal 9 (Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation), Goal 11 (Makes cities and human settlements inclusive, safe, resilient and sustainable), and Goal 12 (Ensure sustainable consumption and production patterns). All three of these SDGs are closely related to the civil engineering discipline, and Goal 12 aims at efficiency in material use and recycling that is highly applicable to concrete, as it is the second most consumed material worldwide next to water.

The conversion of global, international sustainability problems to local, organizational proportions is an actual issue in the literature[7)]. By recognizing that the sectoral indicators for making sustainable concrete can further the achievement of the SDGs, it becomes clear for industry practitioners, designers, specifiers, owners, and other stakeholders to recognize their individual contributions to these set of goals. This validates the importance of the relationship of the SCIs and the SDGs, and expectedly will encourage their usage into the concrete sector. In the next section, an illustration on how this relationship can be quantified is discussed through a demonstration calculation.

3. Demonstration Study

3.1 Selected SCIs and their related SDGs

One eventual outcome of the SCI-SDG relationship clarified in the previous section is the quantification of the SCI's contribution towards a certain goal. This is useful in the decision making process in order to decide the acceptability of the material designed for a particular purpose and function. The following discussion tries to illustrate how this evaluation can be done through a demonstrations study. Pre-selected SCIs in their causal structure shown in Figure 3 were employed, it should be clarified that this is only part of the entire framework from the previous work by the authors[4)]. In this structure, the indicator groups - driving force, state and impact indicators – are retained providing different set of information per indicator group. The dependency and interrelationship of indicators is represented by the lines connecting the SCIs. The associated SDGs of each pre-selected indicators supplementing this figure are shown in the Figure 4, together with the equal weights assigned per indicator group to signify that the indicators are treated as equally important. However, this is just for illustration purposes only, and the issue on importance through indicator weights will be dealt with in detail in a separate paper by the authors.

3.2 Data Analysis

The data utilized is from a study[8)] regarding the use of recycled aggregate (RA) with varying quality expressed in terms of the differences in the density (ρ) and absorption (A). The indicator used to determine the influence of the percentage replacement of RA to natural aggregate is the 28-day compressive strength (fc') equivalent to SCI 17.01. In this paper, we extended the data to include the CO_2 emissions from production (SCI 5.01)

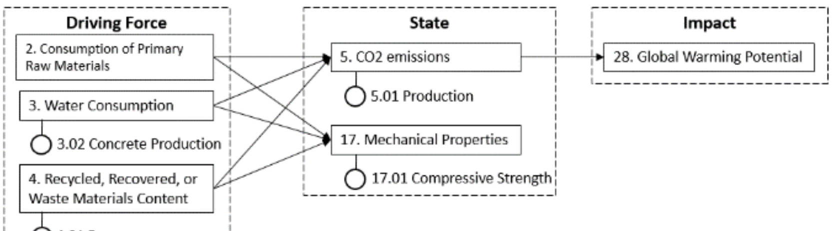

Figure 3 Sample SCIs in causal structure

Table 1 Factors and responses per concrete mix

Series	Factors				Responses		
	W/C	ρ (g/cm³)	A (%)	RA (% Replacement)	fc' (MPa)	CO_2 (kg-CO_2 eq/m³)	GWP_{CO2}
30-N	0.3	2.71	0.78	0	68.21	456	0.46
30-R1	0.3	2.45	5.66	100	51.97	441	0.44
50-N	0.5	2.71	0.78	0	41.87	276	0.28
50-R1	0.5	2.45	5.66	100	32.44	277	0.28
50-R2	0.5	2.38	7.53	100	32.70	257	0.26
50-R3	0.5	2.36	7.91	100	28.79	275	0.28
50-N-R1	0.5	2.58	3.22	50	31.28	274	0.27
50-R1-R3	0.5	2.41	6.79	100	28.65	276	0.28
70-N	0.7	2.71	0.78	0	22.49	202	0.20
70-R1	0.7	2.45	5.66	100	18.87	210	0.21

by theoretically calculating it from existing published inventory data[9], taking only the contributions from cement, sand, natural aggregate, and recycled aggregate. In addition, the GPW (SCI 28) was determined based only on the calculated CO_2 emissions, while neglecting the additional inputs from other contributing sources.

Table 1 summarizes the data used in this demonstration study, showing the factors as the independent variables, and the responses as dependent variables. Three low-grade recycled aggregate type R1, R2, and R3 with densities 2.45, 2.38, and 2.36 (g/cm³) respectively, was used together with natural aggregate (N) as control. Combinations of recycled and natural aggregates were also investigated, shown in the same table. We used the same nomenclature for the series name from the source paper.

To express the responses in terms of the factors, a response surface modeling method was used to empirically determine the relationship of the variables used in this demonstration calculation. This method involves a series of mathematical and statistical computations using Analysis of Variance (ANOVA) and lack of fit test (F-test) to produce a numerical model expressed as series of polynomial terms for a certain factorial experimental data. The empirical equations relating the factors and responses following this method are as follows:

$$CS = -111.47 + 127.35(W/C) + 85.71\rho - 0.26(RA) - 121.35(W/C)\rho + 87.20(W/C)^2 + (2.25\times10^{-3})(RA)^2 \quad (R^2 = 0.9938) \qquad \text{Eq. 1}$$

$$CO_2 = 919.19 - 1979.38(W/C) + 1372.90(W/C)^2 \quad (R^2 = 0.9934) \qquad \text{Eq. 2}$$

$$GWP_{CO2} = (CO_2 \text{ (in tons)}) \times (\text{Characterization factor}) \qquad \text{Eq. 3}$$

The model equations can then be used to predict the behavior of the responses outside the test range, although this calculated by expressing in tons the amount of CO_2 from Eq. 2, and multiplying it with a characterization factor equal to 1.0 for CO_2 gas at 100-yr time horizon. The characterization factor is applied to convert a life cycle inventory (e.g. CO_2 emissions) to the common unit of the category indicator (e.g. GWP)[10]. From the above expressions, it can be observed that the compressive strength is dependent only on W/C, the density, and the percentage of recycled aggregate replacement. Meanwhile, the CO_2 is surprisingly dependent only on W/C, and not on the percent replacement of RA. This independency of CO_2 emissions to the percentage of RA replacement is primarily because the recycled aggregates used are low-grade, with similar CO_2 footprint as the normal aggregate.

Nevertheless, the reader is reminded that since this demonstration calculation is purely used to show the benefits of the causal structure and the SCI's relationship to the SDGs no attempt was made to explain the reason why the results behave as they do from an experimental point of view.

3.3 Demonstration Scenarios

Three driving force indicators (SCI 2, 3, and 4.01), two state indicators (SCI 5.01 and 17.01), and one impact indicator (SCI 28), as shown in Figure 3, were investigated using the empirical equations. In this analysis, we considered only the amount of cement as part of the raw material consumed, and the recycled materials content as the RA percentage replacement. SCI 2 and 3.01 were further reduced into one variable as the W/C. From the relationship expressed in Eq. 2, the dependency of the CO_2 emissions to RA replacement in Figure 3 is not anymore reflected in Figure 4 since it is only dependent on W/C.

Due to the multi-dependency of the compressive strength (fc') on various factors, several scenarios were established to simplify the analysis. Scenario 1 acts as the base scenario, termed as a normal concrete mix with 0% RA replacement and W/C = 0.5. Another is Scenario 2, with RA replacement equal to 50% while using the same water/cement ratio in Scenario 1. The other is Scenario 3, where 50% RA replacement is used and W/C is reduced to 0.4. The density of the recycled aggregate was also pre-set to 2.45g/cm³ equivalent to R1. By substituting these pre-selected amounts to Eq. 1 thru Eq. 3, the resulting indicator values for each scenarios were obtained as shown in Figure 4.

3.4 Analysis of the Causal Relationship of the SCIs

One benefit of using a causal structure in indicator analysis applicable to the scenarios in Figure 4 is that important changes can be observed and traced. By comparing the indicator values of Scenario 1 and 2, increasing the percentage replacement of RA does not directly contribute to the decrease of CO_2 emissions, and in extension does not reduce the GWP. If, for instance, only GWP is used as an indicator, it will not give a clear detail of the impact of the RA, since GWP value remains the same despite increasing the amount of RA. The indicator CO_2 emissions therefore is important to clarify this relationship. The state indicator then points out which driving force indicators are relevant to cause changes in the state values. In this calculation, the relevance of %RA replacement only affects the compressive strength. This traceability exhibited in the causal structure is particularly beneficial in decision making, justifying that the three indicator groups are equally important.

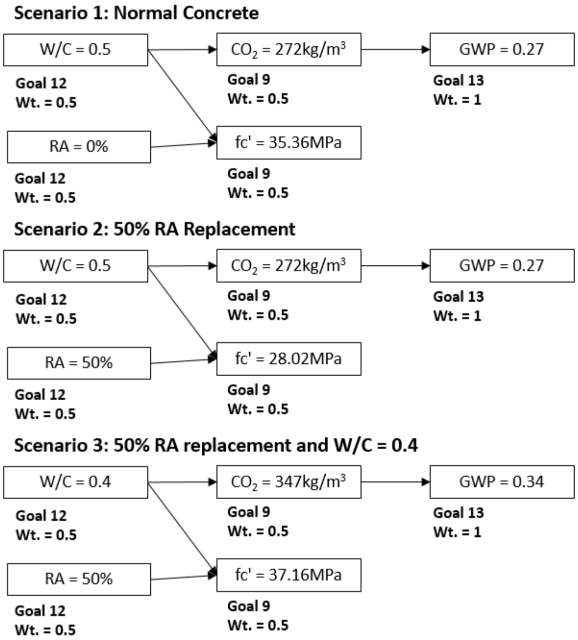

Figure 4 Comparison Scenarios

3.5 Quantifying SCIs' contributions to the SDGs

The potential of the SCIs to affect the SDGs can be observed by the behavior of the indicator values from the base scenario (Scenario 1). Replacing natural aggregates by 50% RA while using the same W/C from Scenario 1, reduces the compressive strength, as in Scenario 2. This reduction negatively impacts Goal 9, while the use of RA in this particular scenario positively contributes to Goal 12. In Scenario 3, to retain the strength level as in Scenario 1, the W/C is reduced, however lower water/cement ratio also means using more cement, thereby increasing the amount of CO_2 emissions which is a negative contribution to Goal 9, and consequently to Goal 13.

The potential effect of an indicator behavior to the SDG can be quantified by calculating the relative beneficial change from the reference values in Scenario 1. The beneficial change for each SDG is the weighted sum of the relative changes in indicator values from the base scenario. For instance, in Scenario 2 for Goal 12, the W/C remained the same, hence the change is 0%, while RA replacement changed to 50%; by multiplying these percent changes by the respective indicator weights and adding the products, the resulting beneficial change therefore is 25%. Note also that positive beneficial change occurs when there is the reduction in indicator values for W/C, CO_2, and GWP, and increase in values for RA replacement and fc'. Figure 5 summarizes this relationship. In this figure, both Scenarios 2 and 3 positively contribute to Goal 12, but at the same time negatively affects Goal 9. Scenario 3 also has negatively impact on Goal 13. This implies the need for crucial judgement to strike a balance between the indicators' contributions to each SDG.

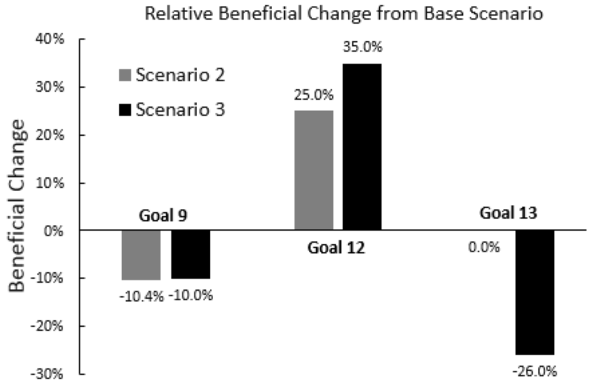

Figure 5 Relative beneficial change in relation to SDGs

4. Conclusion

SCIs prove to be very efficient in translating the complex nature of sustainability, by making the analysis simpler, quantifiable, and easy to communicate. The causal structure of the sustainable concrete indicators shows to be beneficial in clarifying relationships, thereby relaying meaningful information. The SCIs also have universality in terms of its function, since it was shown that they have mutuality with the SDGs' targets. Their behavior also directly influences the sectoral inputs towards the achievement of these goals, and could be made quantifiable, therefore making these contributions less arbitrary, a fundamental character for decision making strategies.

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