学 位 論 文 内 容 の 要 旨
DISSERTATION ABSTRACT

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A multicriteria analytical framework for quantifying the sustainability of concrete materials under methodological uncertainties
(コンクリート材料の持続可能性の定量化に向けた方法論的不確実性を考慮した多基準分析の枠組みの構築)

Concrete is the most widely used construction material that is recognized to have many implications on sustainable development – the interconnection of the three pillars: environment, economy, and society. On one hand, concrete as an integral part of infrastructures supports socio-economic development. On the other hand, concrete uses billions of tons of materials and releases huge amounts of emissions that are injurious to the environment. Making the material sustainable, therefore, is of paramount importance to the industry. Sustainable concrete, however, remains elusive due to the difficulty of conceptualizing concrete from the viewpoint of sustainable development. This necessitates the need for an actionable paradigm that would clarify: 1) What constitutes sustainable concrete? and 2) How to quantify concrete material sustainability to support the decision and policy-making processes? These are the questions resolved in this research work.
The first question requires the building of an indicator framework that distills the conceptual nature of sustainability into measurable components. This framework is developed in this research through the identification of potential sustainability indicators from various literature. A total of 65 quantitative indicators were gathered, most of which describe the environment character of the material. This is evidenced by the abundance of indicators related to environmental measurements, e.g., CO2 emissions, NOX and SOX emissions, particulate matter emissions, and many others. Several economic indicators were also identified such as the unit cost of raw materials, cost of recycled materials, the unit production cost of concrete to mention a few. A number of social indicators were also found such as structural safety, designed service life, human toxicity potential, among others. In-depth analyses, however, revealed an inherent causal relationship between the indicators, which was used to create the causal network of sustainable concrete material indicators (SCMI).
The identification of these sustainability indicators provides a general overview of what constitutes sustainable concrete, operationally answering the first question. To make the indicator framework a robust construct for sustainability assessment applications, the indicators' relationship to the two global perspectives of sustainable development (the three pillars of sustainability and the Sustainable Development Goals (SDGs)) were also clarified. This clarification would provide the governing contextual evaluation perspective. This is also significant to stakeholders so that they can evaluate if their strategies, proposed solutions, and decisions would support the global sustainability agenda.
Answering the second question involved finding ways on how the indicator framework can be utilized to make quantitative evaluations of the sustainability performance of concrete materials. The architecture of the multicriteria decision analysis (MCDA) – henceforth MA – was found to be the most suitable analytical tool for this purpose due to the strong similarity of the sustainable concrete problem

with the multicriteria analytical set-up. The steps of MA are comprised of the selection of indicators, data treatment, normalization, weighting, and aggregation. The selection of indicators defines the extent of the analysis. Data treatment assures the suitability of the data for the analysis. Normalization transforms disparate indicators into a comparable unit and scale. Indicator weighting is the assignment of importance to indicators. Aggregation combines the indicators to a composite value.

MA, however, is not unique as many approaches could be used to perform each step. This multiplicity is recognized as a source of uncertainty in MA as depending on the method used for the evaluation, different conclusions and decisions could result, leading to output uncertainty. In order to create a robust evaluation method, the uncertainties of MA is managed operationally by integrating uncertainty analysis (UA) and sensitivity analysis (SA). UA propagates the input uncertainties to the output, while SA measures the magnitude of influence of the sources of uncertainties to the output. This beneficial to assess whether some uncertainties can be systematically eliminated to increase the robustness of the whole evaluation system.

The reduction of uncertainty is achieved by following a set of statistical rules, i.e., the Kolmogorov-Smirnov D-statistic was used to measure the effect of eliminating a source of uncertainty. In addition, the Dvoretzky-Kiefer-Wolfowitz inequality bound was also utilized to corroborate the result of uncertainty reduction. The decision component of the evaluation system is characterized by the inclusion of a probabilistic hierarchical ordering method. This is practical for comparing sustainability performance when the result is affected by uncertainties. The method assigns relative probability values to each alternative while preserving the output uncertainty, allowing direct identification of the "best" sustainable option. The combination of MA, UA and SA other statistical tools and the probabilistic ordering together create the sustainability evaluation framework for concrete material.

The practical implementation of the indicator framework and the sustainability evaluation framework was demonstrated by comparing the sustainability performance of various concrete materials. Both frameworks were found to perform well in various scenarios examined, which considers the effect of the environment on the durability of concrete materials and the issues on missing data. In all scenarios, the influences of the uncertainties to the output of the analysis were quantitatively measured. The utilization of the probabilistic ordering of the alternatives was also able to identify the "best" sustainable option despite the presence of uncertainties.

Over the course of the research, many other areas were explored relevant to MA and sustainability quantification in general. One of which is on the use of double weighting to account for data variation as weights from stakeholders in conventional MA completely neglects the structure of the data. The research also explored the application of other advanced modeling tools, such as the use of response surface methodology, desirability analysis, and the combinations of other statistical tools to create an exploratory sustainability evaluation system for concrete dealing with continuous variables. Another is the use of trilateral viewpoint (durability, cost, and environmental performance) as a way to evaluate the sustainability of concrete materials, which also utilize aspects of MA under uncertainties.

The indicator framework and the evaluation framework together with the rich plethora of analytical methodologies presented in this research transformed in a robust way the concept of sustainable concrete into engineering terms that are actionable for various stakeholders of the industry. These outputs are expected to spur innovations in sustainable concrete material design, development standards and specifications, and ultimately assists the stakeholders in reaching critical decisions for the sustainability of concrete material.