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QUANTIFYING UNCERTAINTIES IN THE SUSTAINABILITY EVALUATION OF CONCRETE MATERIALS CONSIDERING REGIONAL CHARACTERISTICS IN JAPAN

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Abstract.

In the evaluation of concrete sustainability, what constitutes "sustainable" to one region may vary from another. This often leads to methodological forms of uncertainties that makes the evaluation process more complex. As such, this paper aims to quantify the effect of uncertainties in the regional context on the sustainability evaluation of concrete materials. This is carried out by quantifying the regional context through establishing a weighting scheme and then integrating the obtained weights into the sustainability analysis of concrete materials in tandem with uncertainty analysis. Japan is used as a case study because although it relatively appears as a homogeneous country, its prefectures possess unique characteristics that may make the sustainability evaluation of concrete materials vary across prefectures. Cluster analysis is carried out in the 47 prefectures of Japan using a set of regional context indicators. Five clusters are identified with varying characteristics and these are translated into different weighting schemes. The established weights are used in the sustainability evaluation of concrete materials using multi-criteria decision-making analysis. The results showed that one mix is the most sustainable for four of the clusters and a different mix is the most sustainable for the remaining cluster. When uncertainty analysis is conducted, the effect of the weights in the sustainability evaluation is explained by examining the average scores of the concrete mixes and the variance of the scores across the five clusters. This investigation facilitated the understanding of how regional differences and the uncertainties associated with it impact the evaluation of concrete sustainability.

Keywords: Regional characteristics, sustainable concrete, uncertainty analysis.

1. Introduction

Sustainable development, commonly defined as "the development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [1], has its implementation dependent on individual governments. Each country has varying context on this concept making the means of attaining sustainability different among countries [2]. With the growing awareness of sustainable development, the concrete industry is taking efforts to participate in the practice of sustainability. Similar to sustainable development, the implementation of sustainability in concrete also varies by region because concrete is a regional context material itself. Henry and Opon [3] introduced a means for quantitatively analyzing the regional context of sustainability and linking this regionality to the sustainability evaluation of concrete materials. However, methodological forms of uncertainties exist in this evaluation which make the evaluation process more complex. As such, it is the goal of this paper to quantify the effect of uncertainties in the regional context on the sustainability evaluation of concrete materials. Japan was used as a case study for this analysis because although Japan appears to be relatively homogeneous as a country, it has 47 prefectures having unique characteristics which may make the sustainability evaluation of concrete materials vary across prefectures.

2. Methodology

The analytical flow adopted in this study is summarized in Figure 1. Initially, a set of quantitative regional context indicators was constructed, gathered for all prefectures and processed accordingly. Then, an agglomerative hierarchical clustering method was used to explain the regional context by identifying groups of prefectures exhibiting similar characteristics. These clusters form the basis of weighting schemes which represent regionality and the obtained weights were used as inputs in the concrete sustainability evaluation of a set of concrete mix utilizing multicriteria decision-making analysis. Finally, the

FIGURE 1. Analytical flow.

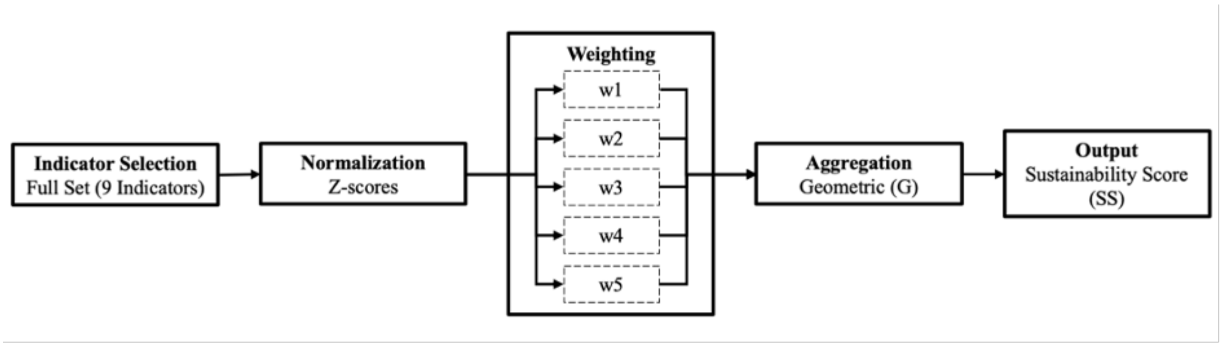

FIGURE 2. Sustainability evaluation framework using MCA.

Range of z-score	$z\leq-3$	$-3<z\leq-2$	$-2<z\leq-1$	$-1<z\leq-0.5$	$-0.5<z<0.5$	$0.5\leq z<1$	$1\leq z<2$	$2\leq z<3$	$3\leq z$
Relative intensity (−)	1/9	1/5	1/3	1/2	1	2	3	5	9
Relative intensity (+)	9	5	3	2	1	1/2	1/3	1/5	1/9

TABLE 1. Conversion of in-cluster mean z-scores to relative intensities for calculation of weights.

effect of methodological uncertainties in the regional context of concrete sustainability evaluation was investigated using uncertainty analysis to understand how these uncertainties influence concrete sustainability evaluation results.

2.1. CLUSTER ANALYSIS METHODOLOGY AND EXTRACTION OF WEIGHTS

In accordance with the guidelines provided by Kassambara [4] for conducting cluster analysis, the agglomerative hierarchical clustering method was adopted using the open source statistical analysis software R [5]. In this approach, the prefectural data was first standardized to a mean of zero and a standard deviation of one converting them to z-scores. After which, the distance matrix which summarizes the distance between any two prefectures in an n dimensional space (where n is the number of indicators) was calculated using the Euclidean distance method. A hierarchical tree was created using a linkage function to group prefectures based on their distance information. Finally, a dendrogram, which is a visualization of the cluster analysis results, was produced and examined for analyzing the regionality of concrete sustainability. The clusters were the basis in the extraction of weights.

Weighting of indicators is an important area in sustainability evaluation as they reflect the significance of different dimensions in their contributions to the sustainability performance of a system [6]. A weighting scheme based on the Analytic Hierarchy Process (AHP) approach was used to reflect regionality in the evaluation of concrete sustainability similar to the method taken by Henry and Opon [3]. AHP is a multi-criteria decision-making tool that structures the decision-making process as a hierarchy composed of quantifiable criteria and their relations and alternatives towards a goal [7]. Weight determination is dependent upon pairwise comparison of indicators and since pairwise comparison is not applicable to negative or zero values, the z-scores were converted to relative intensities following the scale shown in Table 1 depending on the loading direction of the indicator as shown in Table 5.

2.2. CONCRETE SUSTAINABILITY EVALUATION METHODOLOGY

After obtaining the different weights, sustainability evaluation of the concrete mixes was conducted using Multi-Criteria Analysis (MCA) shown in Figure 2. Each step in the framework is explained in the following sections.

Label	Data source	Description (units)
Res1	a	Total cement consumption in concrete per capita (100kg/capita)
Res2	a	Total aggregate consumption in concrete per capita (100kg/capita)
Res3	b	Total water withdrawal per capita (m^3/person)
Res4	c	Usage rate of slag blended cements (0% of total cement consumption)
Res5	c	Usage rate of fly ash blended cements (0% of total cement consumption)
Wst1	d	Total concrete construction waste generated per capita (100kg/person)
Eco1	d	Total construction investment per capita (1000yen/person)
Env1	e	Total CO_2 emissions per capita (tons/person)
Env2	e	Total energy consumption per capita (GJ/person)

Data source: a: Ministry of Economy, Trade and Industry
b: e-Stat
c: Japan Cement Association
d: Ministry of Land, Infrastructure and Transportation
e: Ministry of the Environment

Table 2. Indicators for regional context analysis data from 2010.

2.2.1. Indicator selection

Indicators are selected based on their relevance to what is being measured. They are the fundamental structural basis on which the sustainability of a concrete material can be judged [8].

2.2.2. Normalization

The indicators are expressed in different units. In order for them to work together in an aggregated composite, normalization is necessary. Several methods are available for this purpose but for this paper standardization using z-scores was used.

2.2.3. Weighting

Weighting schemes can sometimes increase or eradicate trade-offs between indicators, which makes weighting a controversial issue in concrete, as current codes are silent about it and still emphasize the hierarchy of mechanical performance [9]. Due to this subjectivity, clarifying how much of an impact the weights have in the concrete sustainability evaluation is demonstrated in this analysis.

2.2.4. Aggregation

Geometric aggregation (G) was chosen as the aggregation method in this paper as it involves aggregation by geometric mean using the product values [8] and is appropriate when less compensability is desired [10]. Equation 1 shows how this is calculated where w is the weight assigned to each indicator and SCI is the indicator normalized value.

$$G = \prod_{i=1}^{n} = (SC_i)^{w_i} \tag{1}$$

Finally, the aggregated values were standardized using z-scores followed by a transformation to t-scores converting the results to a scale of 0 to 100 assuming a mean of 50 and herein referred to as sustainability score (SS).

3. Results and Discussions

3.1. Regional context indicators

For quantifying the regional context of concrete sustainability, a set of 9 indicators was constructed as summarized in Table 2 spanning four categories. The resource consumption indicators (total cement, aggregate and water) and the waste generation indicator (total concrete construction waste) focus on the flow of materials from the beginning to end of its life cycle. The distribution of steel manufacturing and coal power generation within Japan affects the usage of blended cements leading to the inclusion of two additional resource consumption indicators (usage rate of slag blended and fly ash blended cements). Finally, economic and environmental aspects of sustainability were represented with three indicators measuring total construction investment, total CO_2 emissions and total energy consumption. Normalized values (e.g. per capita) were utilized to facilitate comparison of variables that scale with prefectural size.

3.2. Clustering analysis

With the regional context indicators, cluster analysis was carried out to identify groups of prefectures exhibiting similar characteristics. The linkage function used was the average linkage function because it had the highest correlation coefficient of 0.86 between the Euclidean distance matrix of the standardized data and the cophenetic distance matrix among the several linkage functions tested. The dendrogram produced by the clustering result is shown in Figure 3. The authors set the number of clusters to five by cutting the tree at the height shown to sufficiently represent regionality without overly simplifying nor overly complicating the analysis. Clusters are numbered from one to five from the left.

The in-cluster mean z-scores of the five clusters for each regional context indicator are summarized in Table 3. Clusters 1 and 4 are single-membership clusters

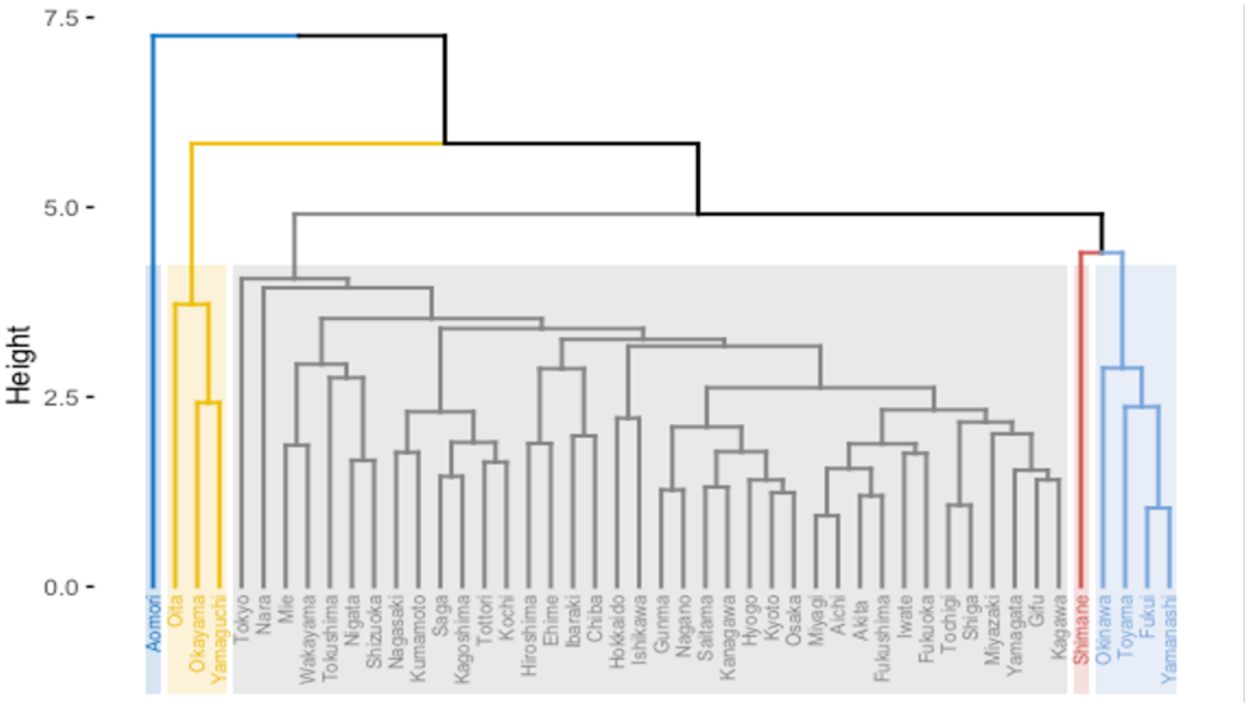

Figure 3. Dendrogram of agglomerative hierarchical clustering results.

Cluster	Res1	Res2	Res3	Res4	Res5	Wst1	Eco1	Env1	Env2
1	0.38	0.45	-0.52	-1.44	6.04	0.31	1.98	-0.18	-0.16
2	0.38	-0.14	-0.17	0.67	-0.24	0.84	-0.39	3.17	3.19
3	-0.28	-0.26	0.04	0.02	-0.12	-0.27	-0.22	-0.19	-0.18
4	1.34	1.02	-1.58	1.29	-0.24	3.69	2.00	-0.37	-0.55
5	1.91	2.20	0.32	-0.67	-0.15	0.92	1.34	-0.42	-0.47

Table 3. In-cluster mean z-scores for regional context indicators by cluster.

containing Aomori and Shimane, respectively, that is the in-cluster mean z-scores of these clusters are the z-scores of the prefecture themselves. The in-cluster mean z-scores explain the distinctive characteristics of each cluster and these were used as inputs in calculating the weights.

3.3. Extraction of weights

The calculated weights are shown in Table 4 and it can be deduced from these results that different clusters put different weights on the indicators. As these values were normalized to have a total sum of 1, it is easier to compare than the in-cluster mean z-scores. Cluster 1 consisting Aomori puts a very high weight on Res5 derived from the high value of the prefecture's fly ash usage rate. Cluster 2 composed of Oita, Okayama and Yamaguchi puts the same emphasis on Env1 and Env2 attributed to the high value of its CO_2 emissions and energy consumption. Cluster 3 containing 38 clusters have equal weighting for all the indicators and can be said to represent the average conditions in Japan. Cluster 4 with only Shimane has its greatest weight on Wst1 associated with its high concrete construction waste. Finally, cluster 5 comprising Okinawa, Toyama, Fukui and Yamanashi has a number of indicators with high weight including Res1, Eco1 and especially Res2 related to its high total aggregate consumption. These weights are parallel with the in-cluster mean z-scores of the clusters.

3.4. Concrete sustainability evaluation

A set of 9 indicators for concrete sustainability evaluation was constructed as shown in Table 5. Each concrete sustainability indicator has its corresponding regional context indicator. The table shows the loading direction of each indicator which indicates the behaviour that contributes to increased sustainability and is employed in the calculation of weights. For example, decreasing the consumption of raw materials improves the sustainability of a concrete mix.

A test set of three concrete mixes was drawn from Noguchi et.al. [11] and the mix proportions are shown in Table 6. To render consistency in the analysis, mixes with 28th day compressive strengths of approximately 30MPa which are generally used for civil engineering infrastructures were chosen. Three new alternatives were created containing high-grade recycled aggregates are also shown in the table. High-grade recycled aggregates were assumed to have the exact same properties and cost as normal aggregates

Cluster	Weight (w)	Res1	Res2	Res3	Res4	Res5	Wst1	Eco1	Env1	Env2
1	w1	0.05	0.05	0.02	0.15	0.44	0.05	0.15	0.05	0.05
2	w2	0.04	0.04	0.04	0.07	0.04	0.07	0.04	0.33	0.33
3	w3	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11
4	w4	0.12	0.12	0.01	0.12	0.04	0.35	0.19	0.04	0.02
5	w5	0.16	0.26	0.05	0.11	0.05	0.11	0.16	0.05	0.05

Table 4. Indicator weights for each cluster.

Label	Indicator	Units	Loading	Related regional context indicator
Cem	Cement content	kg/m^3	–	Res1
Agg	Natural aggregate content	kg/m^3	–	Res2
Wat	Water content	kg/m^3	–	Res3
Bfs	Blast furnace slag content	kg/m^3	+	Res4
Fa	Fly ash content	kg/m^3	+	Res5
Rca	Recycled aggregate content	kg/m^3	+	Wst1
Cst	Construction materials cost	yen/m^3	–	Eco1
CO_2	CO_2 emissions	kg–CO_2/m^3	–	Env1
Ener	Input energy	MJ/m^3	–	Env2

Table 5. Indicators for concrete sustainability evaluation.

Mix	28th day f'_c (MPa)	W/B (–)	W (kg)	C (kg)	BS (kg)	FA (kg)	S (kg)	NA (kg)	RA (kg)
Ref	30.57	0.57	184	325	0	0	783	1063	0
A	30.57	0.57	184	325	0	0	783	0	1063
B1	30.44	0.58	192	200	133	0	806.2	965.4	0
B2	30.44	0.58	192	200	133	0	806.2	0	965.4
F1	30.23	0.56	186.7	238.1	0	94.1	847	949.9	0
F2	30.23	0.56	186.7	238.1	0	94.1	847	0	949.9

Table 6. Concrete mix proportions per m^3.

for simplicity. Thus, concrete with high-grade recycled aggregates have the same properties as mixes with normal aggregates, but the inventory data shows that they require more energy to process to go back to the original state which is reflected by higher CO_2 emissions and energy consumption [12].

Table 7 shows the calculated indicator values for each mix wherein the six constituent material indicators were all determined directly from the mix proportions. Due to the lack of data on the regional variation of the costs of constituent materials, this analysis uses a single value per mix obtained from Henry and Opon [3] and calculated to get the unit cost per mix. Lastly, the two environmental impact indicators were computed using Japanese inventory data [13].

The concrete sustainability evaluation results using MCA are shown in Figure 4. Each cluster's results represent one implementation of MCA. Looking at each cluster, varying weighting schemes lead to varying sustainability scores for the different mixes. For clusters 1, 3, 4 and 5, the most sustainable concrete material is only one mix (F2). While for cluster 2 the most sustainable concrete material is a different mix (B1) whose selection is heavily supported by the high weight placed on CO_2 and Ener indicators by this cluster and among the concrete mixes, mix B1 has the lowest CO_2 emission and energy consumption values. Despite the same most sustainable concrete material for four of the clusters, the ranks of the other mixes change. But, a high level of confidence can be presumed on mix F2 considering a general choice for the most sustainable concrete material for the entire country.

Mix	Cem	Agg	Wat	Bfs	Fa	Rca	Cst	CO_2	Ener
Ref	325	1063	184	0	0	0	5,775.04	255.12	1213
A	325	0	184	0	0	1063	5,775.04	270.86	1563.8
B1	200	965.4	192	133	0	0	5,679.39	162.63	861.84
B2	200	0	192	133	0	965.4	5,679.39	176.92	1180.4
F1	238.1	949.9	186.7	0	94.1	0	5,265.96	190.22	956.62
F2	238.1	0	186.7	0	94.1	949.9	5,265.96	204.28	1270.1

Table 7. Concrete mix characteristics (units are shown in Table 5).

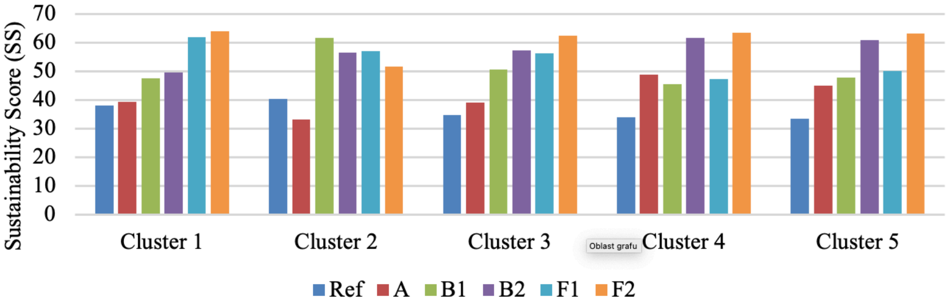

Figure 4. Sustainability scores of concrete mixes by cluster.

Mix	Average SS	$\text{Rank}_{\text{AverageSS}}$	Variance	$\text{Rank}_{\text{Variance}}$
Ref	36.00	6	7.27	1
A	41.08	5	29.11	5
B1	50.55	4	32.62	6
B2	57.09	2	18.46	2
F1	54.41	3	27.18	4
F2	60.87	1	21.61	3

Table 8. Descriptive statistics of uncertainty analysis for each concrete mix.

3.5. Uncertainty analysis

The subject of uncertainty propagation in concrete material sustainability evaluation that arises from weighting schemes is discussed in this section (i.e. how much the weights impact the sustainability evaluation results). The method undertaken for this analysis is where the SS of each mix for all of the clusters were aggregated and the corresponding average and variance together with their individual ranks were computed as shown in Table 8.

When choosing a sustainable concrete material in a national level but at the same time being aware of the existence of the regional context, saying that mix F2 is the most sustainable concrete mix because it is ranked 1st by four out of five clusters has uncertainties associated with it. The uncertainty analysis is a way of quantitatively examining how much consideration of the regional context will affect the selection of a sustainable concrete mix. As an example, Mix F2 was ranked 1st based on the average sustainability score as it showed to be the most sustainable concrete material for four of the clusters, but considering the variance of this selection, it ranked 3$^{\text{rd}}$ which can reasonably be identified as sustainable. However, when looking at mix B2 which ranked 2$^{\text{nd}}$ based on the average sustainability score, it showed a lower variance. This then is where the choice between choosing a moderately scored material with low variance versus a highly scored material with moderate variance comes in. Generally, a mix with higher average sustainability score and lower variability is desired as this entails a more confident result. Based on this idea and referring to Figure 5, the bottom right mix is the most desirable decision and is identified to be mix F2. These results cannot be an output by conducting concrete sustainability evaluation alone. Viewing the mixes in the perspective of uncertainty analysis gives evidence that even though considering regional context in concrete sustainability evaluation as represented by the weights, the most sustainable concrete material for a national level nonetheless shows to be the same material that displayed the most sustainable character in a cluster level.

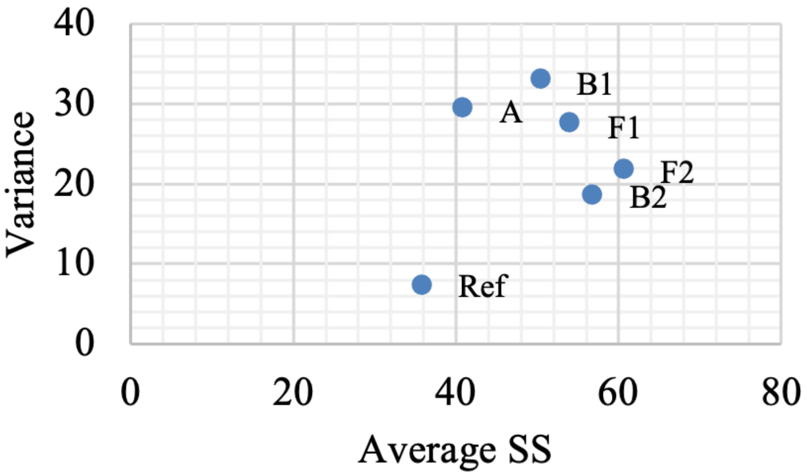

Figure 5. Scatter plot of Average SS vs Variance.

4. Conclusions

In this paper, quantifying the regional context of concrete sustainability was demonstrated that lead to obtaining different weighting schemes. This then was integrated in the evaluation of concrete sustainability. However, uncertainty analysis in this evaluation suggests that those weights, while they can lead to different evaluations of concrete mixes at a mesoscale (cluster level), the effect of the weights potentially may be negligible in a macroscale (national level) considering that the assumptions made in the analysis holds the same and true. This is evidenced by the varied sustainability scores for each mix per cluster, but the rank of the most sustainable concrete material does not change for one mix except in one cluster. With this at hand, it can be concluded that the weights are not leading to a significant difference of the selection of the most sustainable concrete material. Therefore, applying a simple weighting scheme, such as equal weighting, may be sufficient for the representative sustainability evaluation of concrete.

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